Today Science
Tomorrow Defence

DRES

Meeting the Challenge
Defence Research at Suffield

UNLIMITED

Defence Research Establishment Suffield

The mandate of the research and development program of Canada's Department of National Defence (DND) is to support and improve the operational capabilities of the Canadian Forces. The program also encourages technology transfer to Canadian industry.

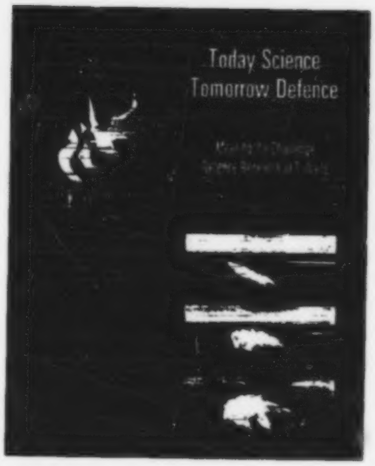
The Chief of Research and Development (CRAD) administers the research and development program, reporting directly to the senior management of DND. CRAD provides ongoing scientific and technical support to DND by calling upon the expertise of the five Defence Research Establishments it operates. Located in Dartmouth (Nova Scotia), Valcartier (Quebec), Ottawa, Toronto, and Suffield (Alberta), they perform research and development across a broad range of defence related problems.

Defence Research Establishment Suffield (DRE Suffield) combines a laboratory environment with the largest experimental range in Canada, to conduct research in defence against chemical and biological weapons and in military engineering.

Meeting the Challenge

DRESuffield is one of Canada's main defence science and technology assets. Established in 1941, when the threat of chemical warfare against Canadian and allied troops was immediate, and the need for defence against such weapons urgent, it expanded into shock and blast physics, aerial targets, meteorology, vehicle mobility and military engineering and other areas to meet the changing requirements of the Canadian Forces. At the same time, work in defence against chemical and biological (CB) warfare agents has continued, ultimately providing the Canadian Forces with defensive equipment that is among the best in the world. Now, DRE Suffield is enhancing Canada's ability to support effective implementation of treaties banning CB agents.

To meet the challenges of the future, DRE Suffield will continue to provide expert technical support to the Canadian Forces and work closely with defence industries. It will expand its links with the industry and leverage its relationship with universities and research institutes to exploit opportunities presented by civilian application of its technologies.



COVER:

The background texture is a colorized smoke record produced by a detonation wave, propagating parallel to a wall.

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Meeting the Challenge
Defence Research at Suffield

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Edited by

C.A. Boulet
Defence Research Establishment Suffield

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Canada

National Defence Défence Nationale

DRES

//DRE SUFFIELD IS COMMITTED TO active, two-way communication with its primary client, the Canadian Forces, its industrial and university partners and the general public. This monograph offers the clients and partners of DRE Suffield a better understanding of its capabilities, expertise and achievements as well as showing the role of research and development in the defence of Canada. //

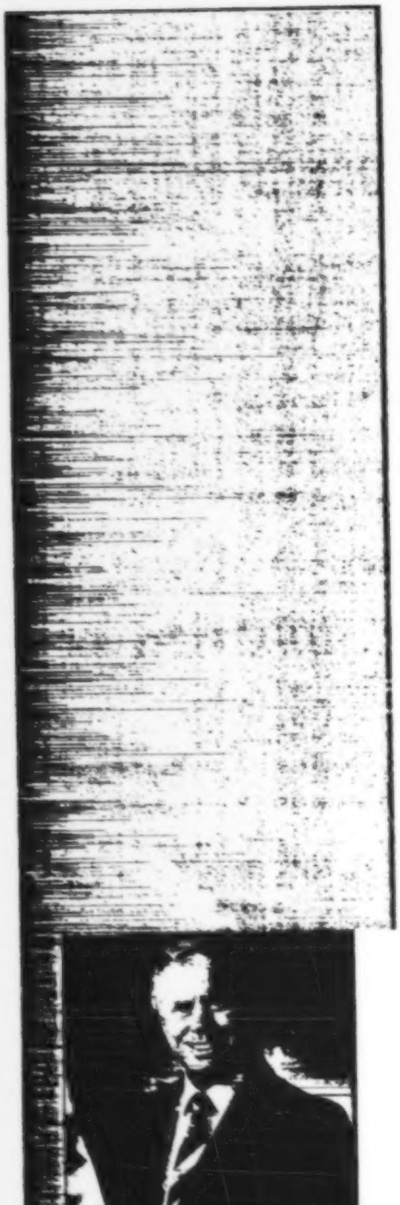
The exceptional capability which resides in DRE Suffield can and must play an important role in serving the future defence needs of Canada. In so doing this capability can and must become an even more effective instrument in the economic development of our nation.

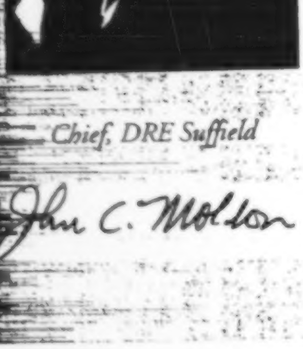
Canadian defence policy is now undergoing an in-depth review which will fundamentally restructure the post-Cold War form of the Canadian Forces and their supporting organizations. An objective of this monograph is to influence the shape of the research and development activity which has been, and must continue to serve as, an integral part of DND's supporting infrastructure.

Knowledge

All R&D laboratories differ to some extent, influenced by the purposes of the organization that they serve. The seven projects described in this monograph illustrate the depth and diversity of the work undertaken at DRE Suffield. All the projects have had a direct and significant effect on improving the operational capability of the Canadian Forces. What is less apparent from the individual papers is that DRE Suffield, along with the other Defence Research Establishments making up DND's R&D branch, is a unique source of expert advice on issues faced by Canadian Forces in the field. The developed scientific and technical knowledge provides the base for informed decisions and the minimization of risk.

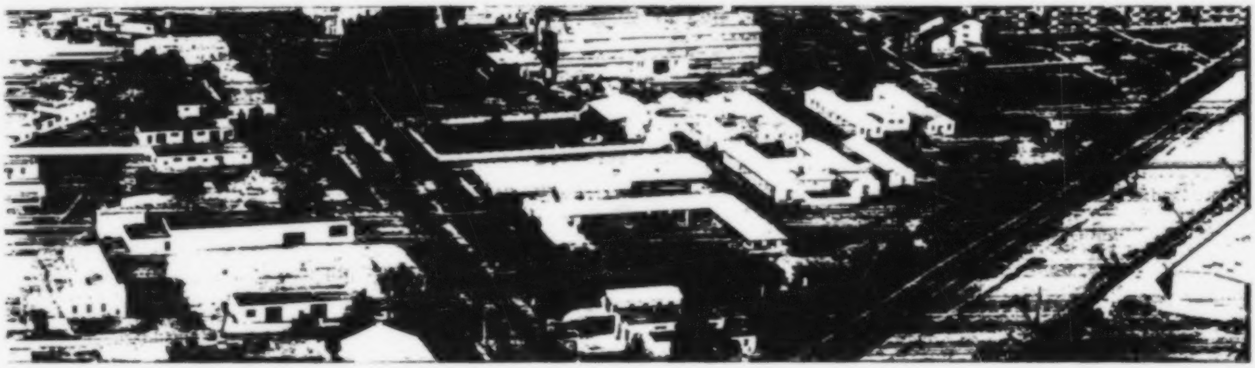
The development of such a reliable base of knowledge has required many years of careful scientific research and the creation of dedicated interdisciplinary teams of scientists and technologists who have been involved in a high degree of cooperation with government, industry and university researchers. The interdisciplinary focus pays off in the migration of skills from one area to another and in improving





Chief, DRE Suffield

John C. Molton



project management capabilities. For example, the work on aerial targets provided some of the technical skills needed to translate a laboratory version of a biological sensor into a fully militarized system.

Collaboration

Although some research, either because of its specialized nature or because of security implications, will be unique to DRE Suffield, the increasing need for highly specialized skills means that future R&D will be much more collaborative than in the past. The sharing will occur in the laboratory research and in the development of capabilities which embody the knowledge obtained through research. This monograph should help to initiate a wider dialogue on collaboration by showing both what DRE Suffield values and what it can do.

It is vital that our military prime clients, the Canadian Forces, understand their stake in maintaining an adequate defence technology base in Canada. It is equally vital that Canadian industry and university communities recognize their responsibility to be part of this technology base and that their membership provides important opportunities for growth in both the defence and civilian markets.

Change

It is increasingly difficult to predict what problems the Canadian Forces will face as recent experience has shown. Although it was known that the Iraqi forces had made use of chemical weapons to repulse Iranian forces and had shown little compunction in using these weapons against their own dissident minority groups, no one had anticipated that Canada would be engaged militarily against this threat in a region so different and distinct from the NATO European theatre, for which most preparations had been directed. The ongoing research at DRE Suffield had created a technology base which was able to provide a rapid and expert response to these new operational requirements. To help protect against the chemical and biological threat, DRE Suffield delivered a battlefield detection system for chemical and biological agents to both Canadian and US Forces deployed in the Gulf.

Interactions

The technological capability of DRE Suffield also plays an important role in maintaining world peace through the support of international conventions such as the Chemical Weapons Treaty. This treaty will be enforceable because there are now the means to detect the manufacture of banned substances, even at very low levels, through the accurate analysis of small samples. Ongoing work will ensure that such treaties may be extended to cover other types of threat.

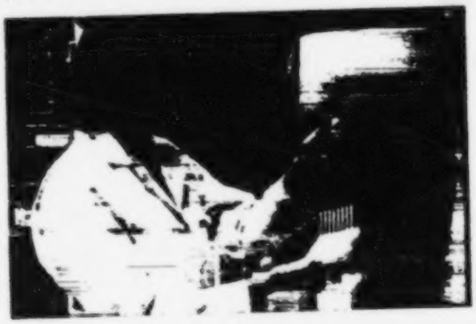
In many of the articles in this monograph reference is made to the interactions between DRE Suffield and industry. The laboratory has acted as a consultant in areas such as explosion risk in the petrochemical industry and in the provision of materials for medical purposes. Other interactions have helped industry deliver the equipment needed by the Canadian and other military forces. Such interactions provide a multiplier effect for the capabilities of the laboratory.

It was noted at the outset that DRE Suffield was committed to dialogue: this monograph tells only the Suffield story but it is hoped that it will become a talking point for all audiences and that the dialogue may thereby be enriched. Technology is relevant to both national security and commercial development and success: knowledge benefits most when it is shared.

TABLE OF CONTENTS

page 3 About the Authors

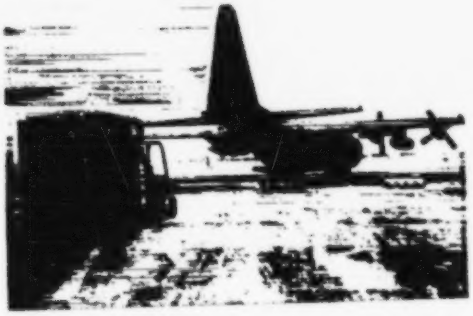
page 6 Introduction



DRE Suffield provides the Canadian Forces with technical expertise in chemical and biological weapons defence, shock and blast physics, aerial targets technology, meteorology, vehicle mobility and military engineering to meet the challenges of continuously evolving technological threats; it offers opportunities to Canadian industries to commercialise its technologies and collaborates with universities on research.

page 11 Detection of Biological Warfare Agents

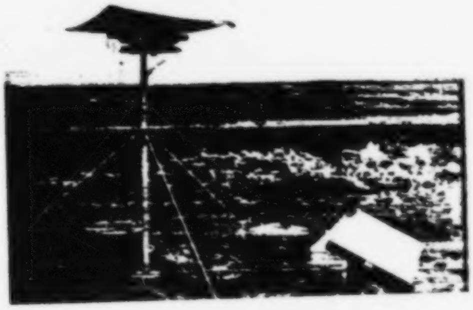
Jim Ho



An early warning system based on an assessment of multiple parameters such as weather conditions, temperature, time of day and particulate size has been developed for the detection of biological agents.

page 19 Remote Detection of Chemical Warfare Agents

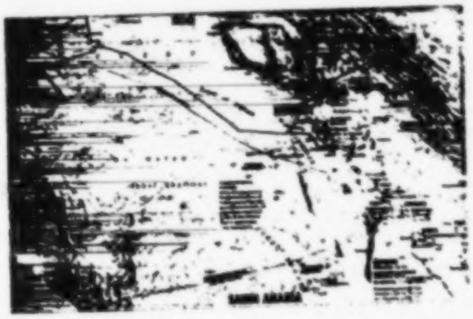
Paul D'Agostino and David Saint



A network of chemical agent monitors can give early warning of a chemical warfare attack; an integrated system was developed and deployed to provide support to Canadian Forces during the Gulf War.

page 27 Field Detection and Identification of Biological Warfare Agents

Alex Markov, Clay Coffey & Al Carruthers



Full protection of Canadian Forces during the Gulf Crisis required the rapid detection and identification of biological warfare agents; an integrated system to perform this function was developed and deployed within a very short period.

page 35

Reactive Skin Decontaminant Lotion

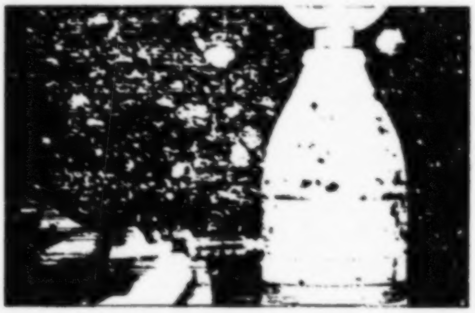
J. Garfield Purdon

Personal protection against chemical warfare agents requires a rapid and effective means of destroying toxic substances; a lotion has been developed to provide Canadian Forces a high degree of protection against chemical weapons.

page 45

Verification of the United Nations Chemical Weapons Convention

Paul D'Agostino, Camille Boulet, & James Hancock

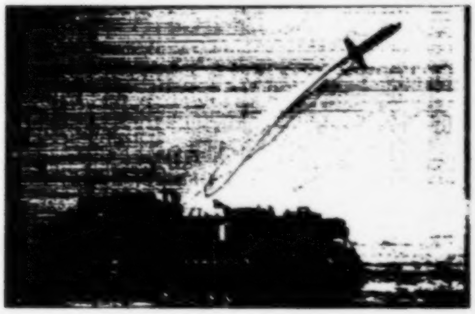


For the effective implementation of a convention abolishing chemical weapons, unambiguous methods for the identification of chemical warfare agents will be required; DRE Suffield is one of the leading laboratories in a world wide effort to develop such procedures.

page 59

Fuel-Air Explosives

Stephen Murray

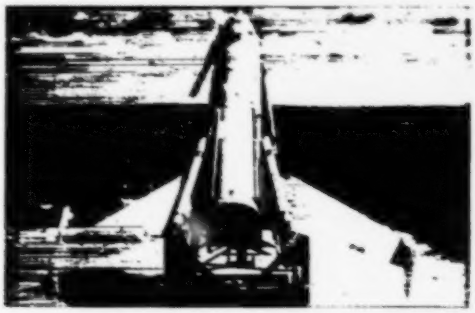


Understanding the basics provides the key to harnessing the power of explosives; the expertise developed at DRE Suffield has wide applications ranging from defence against mines to flame arrestors.

page 75

Aerial Targets

Alex Markov, Robert Herring & Clay Coffey



Defence and training against sophisticated missile attacks requires equally sophisticated aerial targets; this technology developed at Suffield provides commercial opportunities for Canadian industry.

CAMILLE A. BOULET

B.Sc. (Pharmacy) – University of Alberta (1981), Ph.D. (Organic Chemistry) – University of Victoria (1986) is Head of the Biological Detection Group. His research in the area of CW defence includes the development of personnel decontamination systems for CW agents and for the large scale demilitarization of nerve and blister agents. He has compiled spectroscopic databases for identification and verification and developed chain of custody protocols for the handling of samples within designated laboratories. Dr. Boulet has also examined the role of designated laboratories for the analysis of samples for the Technical Secretariat of the Organization for the Prohibition of Chemical Weapons. He served as the Canadian representative to the Technical Group on Instrumentation of the Ad Hoc Committee on Chemical Weapons, Conference on Disarmament, Geneva.

MAJOR A. R. (AL) CARRUTHERS

B.Sc. (Geology) – Brandon University. is a member of the Royal Canadian Engineers and has served in 3 Field Squadron and 1 Combat Engineer Regiments. His military background includes the Land Forces Command and Staff Course at Kingston and the Weapons Staff Course, R.M.C.S, UK. He has been posted to United Nations Military Observer Group India-Pakistan (75-76) and United Nations Iran-Iraq Military Observer Group (88-89). In 1992, Maj. Carruthers was attached to the UN Special Commission for the destruction of nerve agent munitions. For the last 14 years he has worked on engineering, research, and development of combat engineer equipment and explosive systems. In 1985 he was posted to DRE Suffield and again in 1989 after the UN tour in Iran-Iraq.

CLAYTON G. COFFEY

Aeronautical Engineering Technologist – Ryerson Institute of Technology (1960) is a member of the Systems Integration Group, responsible for the design, integration and testing of a variety of aero-mechanical systems, from autonomous unmanned aerial vehicles to the Mobile Atmospheric Sampling and Identification Facility (MASIF). Recent activities included conversion of a rocket boosted target into a turbojet flying laboratory configuration. Mr. Coffey has also worked in the private sector. He was a principal investigator in a number of projects that lead to granting of patents to the DND.

PAUL A. D'AGOSTINO

B.Sc. (Chemistry) 1979, Ph.D. (Analytical Chemistry) , McMaster University (1983) is Head of the Chemical/Biological Identification Group. His research interest is in the development and application of mass spectrometric and chromatographic methods for the identification of chemical warfare agents and related compounds. He has published extensively in this area and was the lead scientist in the multinational round robin analytical exercises organized by the North Atlantic Treaty Organization (NATO) and the United Nations. Dr. D'Agostino represented Canada on a NATO Mid-Term Scientific Study on Methods and Techniques for Chemical Warfare Agent Monitoring, and on United States/United Kingdom/Canada International Task Forces dealing with the Weathering and Decay of Chemical/Biological Contamination and Technologies for Chemical Weapons Convention Verification. He serves as the secretary for the Canadian Society for Mass Spectrometry.

JAMES R. HANCOCK

B.Sc. (Hons. Chemistry) – Dalhousie University (1979), M.Sc. (Analytical Chemistry) – Dalhousie University (1985) is an analytical chemist in the Chemical/ Biological Identification Group. His expertise includes the sampling and identification of chemical warfare agents and related compounds from environmental and man made matrices. Mr. Hancock is currently the Canadian representative to NATO's group of experts on the sampling and identification of chemical agents (SICA). Mr. Hancock is co-inventor and holds patents on the Minitube Air Sampling System, an integrated air sampling and analysis system, that combines solid adsorbent sampling tubes and thermal desorption gas chromatographic analysis.

ROBERT W. HERRING

B.Sc. (Hon Physics) – University of British Columbia (1964), M.Sc. (Upper Atmospheric Physics) – University of Saskatchewan (1967), Ph.D. (Upper Atmospheric Physics) – University of Western Ontario (1977) is a scientist in the Systems Integration Group. His expertise includes design and application of sophisticated algorithms to data from low-cost inertial and other sensors. He has worked in a variety of fields including propagation of radio waves through plasma and radar target detection. Dr. Herring has served as a staff officer in National Defence Headquarters for the Chief of Research and Development in the area of naval radar development.

JIM HO

B.Sc., M.Sc. (Microbiology) McGill University – (1971), Ph D. (Microbiology) – University of Kentucky (1977) Dr. Ho is a scientist with the CB defence section at DRE Suffield. He is recognised by the international defence community as a leading expert in the field of rapid detection of biological aerosols. He is a member of TTCP-EAG-36 and a Focus Officer for the BCD-ACM inlet nozzle. He has presented a plenary lecture on the behaviour and measurement of airborne microorganisms at the European Aerosol Conference in Oxford, England. He is a co-editor of the Journal of Aerosol Science for the special issue on biological aerosols to be published in 1994. Dr. Ho has also been appointed to the board of directors for the Journal of Aerosol Science. For having served in the Gulf War, he (along with other team members from DRES) was awarded a campaign medal by the Canadian Armed Forces, a civilian historical first. The Saudi Arabian Government also presented him a similar award.

ALEX B. MARKOV

B.A.Sc. (1976, Honours) in Engineering Science (Aerospace Option) University of Toronto, M.A.Sc. (1977) and Ph.D. (1981) Flight Dynamics-University of Toronto Institute for Aerospace Studies. Dr. Markov is Head/Systems Integration Group (SIG) in Defence Technologies Division. He is responsible for a variety of advanced technology and system integration projects including the proof-of-concept integration of novel guidance and control systems and algorithms for unmanned air vehicles, support to the CF in above surface guided weapon effectiveness monitoring, and conduct of collaborative research on a number of flying laboratories. Recent work has included the development of a turbojet configuration of the HATT-X flying laboratory drone and leadership of Mobile Atmospheric Sampling and Identification Facility teams. Dr. Markov represents DND on national and international committees and organizations, and is Canadian National Leader on TTCP Technical Panel W-5.

STEPHEN B. MURRAY

B.Eng. (1975), M.Eng. Carleton University (1976), Ph.D. McGill University (1985) has been a Defence Scientist at DRE Suffield since 1976. During the first three years of his career, he was a member of a small R&D team responsible for developing an infrared suppression system enabling warships to avoid detection by heat seeking missiles. This technology has been retrofitted to DDH 280 class destroyers and has been integrated into the new Canadian Patrol Frigate. In 1979, Dr. Murray proposed and initiated a new technology base program in the area of fuel-air explosives. The program has been successful in the areas of explosive minefield breaching and weapon threat assessment, and has established DRE Suffield as a world leader in dispersed explosives technology. Dr. Murray has represented Canada at the Organization for Economic Cooperation and Development, The Technical Cooperation Program, NATO, and in international collaborations with the United States, the United Kingdom, the Netherlands and Norway.

J. GARFIELD PURDON

FCIC, B.Sc. (Hons) - Queen's (1967), Ph.D. (Physical Chemistry) - Toronto (1974) is Head of Decontamination Research. In 1977, after working at the National Research Council and Lumonics Research Ltd., he joined DRE Ottawa in research involved with developing a broad-spectrum protective barrier cream for skin which led to the current decontaminating lotion. He also collaborated in the development of standardized decontamination assessment equipment and methodology. For this work he received a TTCP Achievement Award in 1993. In 1988, he moved the decontamination research effort to DRE Suffield where he is involved in the development of decontaminants and contamination control materials for equipment and research into passive decontamination and weathering processes. In addition to these duties, Dr. Purdon is Canadian National Leader on the TTCP Technical Panel ETP-8 (Contamination Control).

DEFENCE RESEARCH ESTABLISHMENT SUFFIELD

A Tradition of Accomplishment

DEFENCE RESEARCH ESTABLISHMENT Suffield (DRE Suffield) is one of Canada's main defence science and technology assets. It was established in 1941, during the early crisis days of World War II, when the threat of chemical warfare to Canada and her allies was very real and the need to develop defences against such agents urgent.

Following the war, research and development programs at DRE Suffield expanded to meet the changing requirements of the Canadian Forces and included shock and blast physics, meteorology, vehicle mobility, and military engineering. Canadian research in defence against chemical and biological warfare (CB) agents continued to ultimately provide the Canadian Forces with defensive equipment that is among the best in the world.

Today DRE Suffield conducts a vigorous and innovative research program in a number of scientific areas and is the lead authority in Canada's Department of National Defence on a variety of critical military technologies. Defence science is a diverse and challenging area of research. It includes the investigation of fundamental scientific principles and the development of sophisticated military technologies. This monograph is intended to give the reader a greater insight into the research and development activities of DRE Suffield. Each article demonstrates how leading edge research, today's science, can be translated into products for the Canadian Forces, tomorrow's defence.

THE SUFFIELD RANGE
A Unique Canadian Resource

The Suffield Range, 2,690 square kilometres, is a unique area – in size, terrain, and inhabitants. Defence research experiments, military live fire training, cattle grazing, oil and gas development, wildlife management, land reclamation and protection of ecologically sensitive areas – all take place concurrently on this large tract of land.

The DRE Suffield Experimental Proving Ground (EPG) occupies slightly less than one-fifth of the Range, some 431 square kilometres. Over the years, the EPG has been an essential factor in a great variety of studies. These studies include investigations of the effects of air blasts on panels used in the construction of naval ships, the evaluation of the capabilities of military equipment to function in a chemical environment, and the development of ordnance and mine detection equipment. The EPG is also used by industry and defence contractors who require the large land area and the specialized expertise available only at DRE Suffield.

The Canadian Forces maintain training, research, and development programs for defence against chemical and biological warfare threats. Training in self-protection under authentic conditions is essential for all Canadian Forces personnel. DRE Suffield contributes by designing exercises conducted on its EPG where realistic scenarios use small amounts of chemical warfare agent under very controlled conditions.

LEADERSHIP IN SPECIALIZED RESEARCH & DEVELOPMENT

As the needs of DND have changed over the years, DRE Suffield has remained a strategic defence resource. For several decades, DRE Suffield has provided the Canadian Forces with equipment, materials and procedures to defend against the lethal and debilitating effects of CB agents on the battlefield. Now, DRE Suffield is also enhancing Canada's ability to support effective treaties to ban CB weapons. In addition to working closely with the United Nations, DRE Suffield collaborates with its counterparts in NATO countries, as well as Australia and New Zealand, and has formal agreements to exchange information with defence scientific organizations in several countries.

> *As the needs of DND have changed over the years, DRE Suffield has remained a strategic defence resource.*

Many of the research and development activities at DRE Suffield are unique. About half of the scientific effort is directed to the defence technologies which encompass a broad variety of activities generally related to military engineering, mobility systems and weapons system evaluation. The other half of DRE Suffield's scientific activities is generally related to CB defence. Scientific and technological activities are supported by a full complement of services – from meteorology, photography and field support to information services, facilities design and development, and material management.

What DRE Suffield produces often has application for use beyond the military community. For example, air sampling equipment used in the detection of airborne chemical and biological warfare agents has practical applications for air quality monitoring in industrial environmental programs. Fuel-air explosion suppression devices have a use in oil and gas transportation. Snow measurement techniques developed for the study of off-road vehicle mobility are also used in avalanche control.

Over the years, DRE Suffield has generated a considerable, unmatched reservoir of knowledge – not only of CB agents, their toxicology and infectivity, but of the behaviour of liquids, gases and aerosols released in the atmosphere. Information developed by and available at DRE Suffield is of great value to environmentalists, meteorologists, public health authorities and industrial chemists, as well as the Canadian Forces.

> *Canadian research in defence against chemical and biological warfare (CB) agents continued to ultimately provide the Canadian Forces with defensive equipment that is among the best in the world.*

DEFENCE SCIENCES
Canada at the forefront of CB defence

In the Defence Sciences Division, there are five main thrusts to the CB research program:

- hazard assessment
- detection and identification
- physical protection
- medical countermeasures
- verification technology.

CB warfare continues to pose an ever present danger to the Canadian Forces in their worldwide peacekeeping assignments. In the recent Gulf War, DRE Suffield demonstrated its ability to deploy CB defence equipment for the Canadian Forces. An antidote for nerve agent, a skin decontaminant, a CB agent sampling kit, and detectors for CB agents – all were direct applications of ongoing research projects at DRE Suffield. Although the Canadian Forces are well equipped with protective equipment, such as respirators and suits to defend against CB warfare agents, devices to provide a timely warning of imminent biological warfare attack were not available at the outbreak of the war. Research into methods for the detection of biological particles was a focus of the Defence Sciences program. Fundamental aerosol research at DRE Suffield was taken from the laboratory to the field to provide a biological agent detection capability as described in *Detection of Biological Warfare Agents.*

Within weeks, DRE Suffield turned laboratory protocols for biological agent detection and identification into portable field units – creating a fully operational system. In the article ***Field Detection and Identification of Biological Warfare Agents***, the rapid development of a rugged, fieldable prototype system which integrated many laboratory and analytical methods is described. The intense effort required to ruggedize, integrate and deploy the equipment involved virtually all sections of DRE Suffield and CFB Suffield, as well as a number of industrial contractors.

A chemical agent detector and alarm system (CADS) was also developed, utilizing the in-service chemical agent monitor. The alarm system consists of an array of remote sensor stations, sited upwind and connected to a central control unit. By building on existing chemical agents detection systems and in-house electronic expertise, the usefulness of the handheld chemical agent monitor was extended to address an immediate Canadian Forces requirement. These key achievements are described in *Remote Detection of Chemical Warfare Agents.*

Both detection systems were deployed at Canadian Forces facilities in Qatar and Bahrain, and at a U.S. military field hospital in Bahrain, resulting in a significant improvement in defence capabilities. These measures allowed the Canadian

Forces to return to normal operations with protective equipment at the ready and to discontinue taking an antibiotic which had unpleasant side effects. The detection unit in Bahrain was also utilized as a pollution monitor to collect samples and measure particulate concentrations associated with oil well fires in Kuwait.

An important item developed by DRE Suffield and deployed in the Gulf conflict was the Reactive Skin Decontaminant (RSD) lotion. Until development of the RSD lotion, the most widely used skin decontaminant was Fuller's Earth, a powder that absorbed but did not destroy chemical agents. ***Reactive Skin Decontaminant Lotion*** demonstrates how systematic research into the basic chemistry of chemical warfare agent destruction led to a revolutionary product. The RSD lotion safely decontaminates the skin by instantly destroying the chemical agent. It does not create dust and is non-toxic, easy to apply, economical and effective against a wide range of chemical agents.

> *The ability to correctly identify banned substances in a highly reliable fashion will help implement a verifiable treaty and assure compliance.*

Canada is committed to United Nations efforts to put in place an effective and verifiable treaty to ban chemical weapons and to improve the existing treaty prohibiting biological weapons. The development of extremely sensitive detection and identification methods and technologies for CB agents for the Canadian Forces also allowed DRE Suffield to make a unique contribution towards treaty verification as well. ***Verification of the United Nations Chemical Weapons Convention*** demonstrates that the ability to correctly identify banned substances in a highly reliable fashion will help implement a verifiable treaty and assure compliance.

The primary role of biomedical sciences at DRE Suffield is to develop measures to identify, evaluate, prevent and treat the toxic effects of CB agents. The emphasis of this research is on prevention and treatment which can be conducted in the field, preferably by the individual soldier. Because of the nature of CB agents, this research also has significant impact and application in areas of public health and disease control. For example, DRE Suffield is developing techniques to rapidly diagnose infections, particularly those causing meningitis, brucellosis and tularaemia.

In biomedical research, as in all other areas, DRE Suffield takes advantage of the most recent advances in technology. For example, development of tissue cultures has increasingly replaced the use of animals in experiments. The most recent advances in biotechnology have been applied to the solution of problems in medical treatment of CB casualties.

Some research initiatives focus on the development of recombinant vaccines to combat highly pathogenic viruses which could be used as biological warfare agents but which also are public health concerns. For example, DRE Suffield is collaborating with the U.S. Public Health Service to develop a vaccine for western equine encephalitis, a disease which attacks the central nervous system. Commonly referred to as sleeping sickness, it affects both horses and humans, and is endemic to western Canada and the midwestern United States.

As a method of treatment, liposomes are being investigated for the delivery of antibiotics, antibodies and vaccines. With this technology, drugs can be targeted to specific tissues, a particularly useful method for the treatment of diseases such as brucellosis in which the organism hides in the bone marrow or in white blood cells.

The medical research program also includes studies of the transmission as aerosols of naturally occurring respiratory diseases such as influenza, the common cold and meningitis. As well, DRE Suffield is participating in an international research program involving almost 80 labs worldwide in tests to determine toxicity levels for 50 common drug/solvent/heavy metal poisons. The tests are being conducted *in vitro* and with computer modelling. These are a few examples of how defence research contributes to the general pool of world scientific knowledge.

DEFENCE TECHNOLOGIES
Innovative Responses to Technological Challenges

The Defence Technologies Division conducts engineering research and focuses on the following areas:

- obstacle clearance and minefield breaching
- vehicle mobility in off-road environments
- remotely piloted and robotic vehicles
- applications of explosives and structural response to shock and blast
- ordnance detection
- weapons system evaluation.

For many years, the unique advantage of the DRE Suffield EPG was exploited by DRE Suffield scientists studying the effects of large explosive charge detonations. More recently, the development of a national facility called the 1.8 Metre Blast Tube, the largest blast simulation facility in Canada, has enabled the study of shock and blast effects on structures and materials in a controlled and environmentally benign manner. Studies using this facility, often in international collaboration, have led to the development of computer workstations for use by naval architects in the design of vessels such as the Canadian Patrol Frigate to assess structural response and vulnerability.

The development of innovative explosive technology and systems that will extend and improve the operational capability of military engineers in demolitions, barrier production and minefield breaching is undertaken by Defence Technologies Division. Investigations of such phenomena as fuel-air explosions has allowed DRE Suffield to develop theoretical models for explosion propagation. This practical and theoretical knowledge described in *Fuel-Air Explosives* has been applied to a number of problems and provides a sound foundation for the investigation of other explosive phenomena.

Laboratory research and advanced engineering concepts are integrated and translated into knowledge and products for the Canadian Forces.

DRE Suffield has a capability to design explosive charges which can form and accelerate massive metal projectiles at hypersonic velocities. Known as Explosively Formed Projectiles, these have numerous uses such as anti-armour devices and remote demolition of structures such as bridges. This research is dependent on a state-of-the-art capability in the computer modelling of the behaviour of metals deforming at extreme rates of strain, and leads to new understanding of metallurgical processes occurring in the interaction of detonation waves with metallic samples.

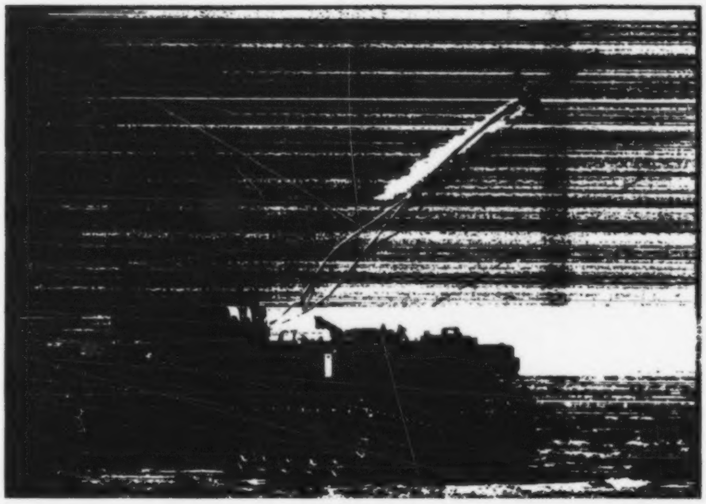
The detection of buried objects has always been a challenging problem to combat engineers, as well as to countries faced with the problem of land contaminated by unexploded ordnance – artillery rounds, mortar shells, bombs and mines. Conventional range clearance methods, which have not changed dramatically since the 1930's, are very time and labour intensive, primarily because of the presence of harmless metal fragments (clutter) in addition to potentially harmful unexploded ordnance.

DRE Suffield is developing "smart" instruments which will be insensitive to clutter and able to accurately locate and identify compact metal objects, classifying them as harmful or harmless. Smart ordnance detectors mounted on vehicles are used to rapidly detect subsurface metal and then, subsequent to this, to locate and identify objects down to two metres. The challenge which DRE Suffield scientists are now addressing is the detection and neutralization of non-metallic mines.

The need for a rapid, efficient means to create a safe path through minefields for both personnel and vehicles has arisen from the rapid expansion of the land mine threat in modern warfare. DRE Suffield scientists have developed systems such as the FALCON (Fuel-Air Line Charge Ordnance Neutralizer) which is capable of breaching a 200 metre lane for vehicles through terrain strewn with mines.

Since the late 1970's, DRE Suffield has conducted research and development into weapon systems evaluation with an emphasis on representative and cost-effective aerial targets. Experimental flight vehicles serve as flying platforms on which to investigate and demonstrate a variety of emerging technologies to provide agile supersonic flight, perform evasive measures and take "intelligent" countermeasures. *Aerial Targets* illustrates the evolution of target vehicles which meet a wide range of performance and cost requirements and serves as a basis for the evolution of further generations of robotic systems.

In addition to its work on smart unmanned aerial vehicles, DRE Suffield is involved in areas of machine intelligence and robotic movement control for land vehicles. Devising an intelligent land vehicle capable of performing tasks such as hazardous materials handling, reconnaissance and surveillance,

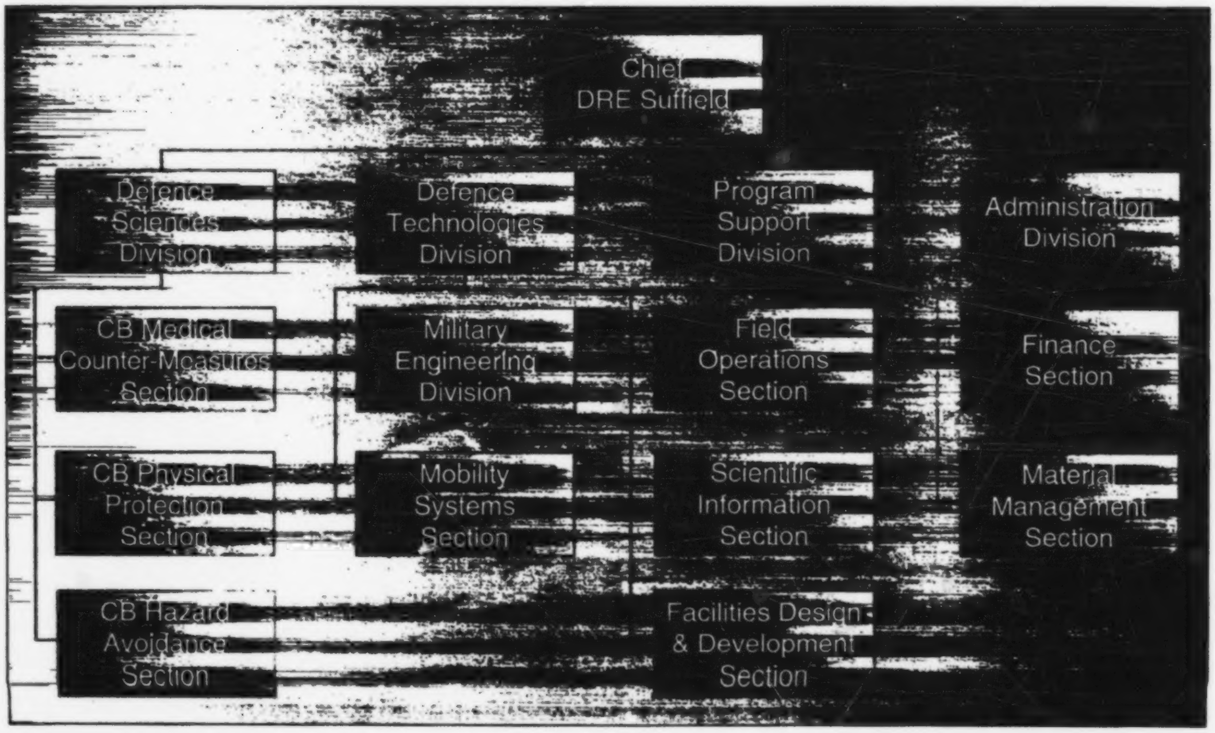


and minefield breaching involves research in many technologies.

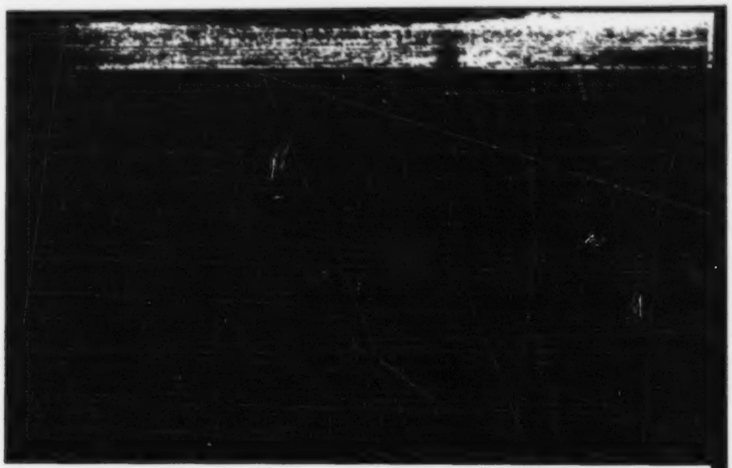
Drawing on an extensive background in vehicle mobility and guidance, DRE Suffield scientists are now looking into new robotic land platforms and controllers which are more mobile, stable and autonomous than existing systems – and thus more versatile. For example, very stable and smooth platforms are being developed which use an active suspension system. Such a platform uses ultrasonic beams to look at the ground ahead of the vehicle, to anticipate wheel movements needed to cross rough terrain and to drive the suspension accordingly to smooth out the ride. Research into improved active suspension systems uses artificial intelligence to replace conventional control systems.

Vehicles using stereo vision and robot arm manipulators controlled by telepresence and an advanced control station to improve human interaction are also being developed. Research on machine intelligence is focussing on the use of neural networks that use many sensor inputs to generate vehicle control signals.

The articles presented in this monograph are not intended to provide an exhaustive review of each research program or detailed scientific information. The vast majority of the research at DRE Suffield is published in the open literature. These articles are an insight into the capabilities and achievements of the scientists and engineers at DRE Suffield. Each is an illustration of how laboratory research and advanced engineering concepts are integrated and translated into knowledge and products for the Canadian Forces and the Department of National Defence.


Chief
DRE Suffield
Defence Sciences Division
Defence Technologies Division
Program Support Division
Administration Division
CB Medical Counter-Measures Section
Military Engineering Division
Field Operations Section
Finance Section
CB Physical Protection Section
Mobility Systems Section
Scientific Information Section
Material Management Section
CB Hazard Avoidance Section
Facilities Design & Development Section

mobile early warning system for detection of the threat from biological warfare agents has been developed from concept to final implementation.



by Jim Ho

The use of chemical weapons in the Iran Iraq War demonstrated the need to continue development of defensive and protective mechanisms against chemical and biological warfare agents. A number of countries are known to have produced biological warfare (BW) agents which may be used against Canadian and Allied Forces in times of conflict. Although the Canadian Forces are well equipped with protective devices such as respirators and suits for chemical and biological agents, a timely warning of imminent BW attack will enhance their effective use.

BW agents are derived from bacterial cultures either in the form of vegetative cells or spores. In addition, viral cultures may also be used as BW agents. The major characteristic of these threat agents is that only about 10 viable organisms per person are required to cause an infection.

Biological toxins are non-living material produced by microorganisms. They are also potential BW agents and may be used in place of chemical agents. Compared to the typical chemical agents, considerably less toxin material is required to incapacitate a victim, making this class of agents more efficient and thus a greater threat.

To be effective against a target, BW agents are most likely to exist as solid particles in air (aerosols) and range in diameter from 0.5 to 15 micrometers (µm). Particles of this size range are able to penetrate the lungs and are called "respirable". Due to the small particle size and the typical concentrations, such an aerosol cloud is invisible to the naked eye and thus difficult to detect. The material can either be disseminated as a powder or as solids in liquid droplets which eventually dry up to become small particles. These particles may travel long distances downwind to become a threat to the target forces.

In the mid-1970s, the US developed a biological detector system consisting of a detection module (XM19) and a sample collection module (XM2). Using chemiluminescence wet chemistry technology, the system measured the presence of biological iron in aerosol particles impacted on a moving tape. It was thought that biological threats of bacterial origin would contain bound iron in the form of hemes such as cytochrome molecules. The XM19 was used in field trials both on land and at sea. It was found that endogenous biological iron in ambient air could set off the alarm and the false alarm rates were considered unacceptably high. For this reason, the US Army rejected the XM19 and no new detectors have since been made. The complexity of the problem and a perception of reduced threat after the treaty banning use of the BW agents in the seventies meant no further progress on biological detectors was reported. The Iran Iraq war changed this perception and the need for such detectors. The Canadian Forces have identified a continuing requirement for biological warfare detectors.

In the early 1980s, our team at DRE Suffield formulated the basic principle of a BW agents detection system. To make the task manageable, it was felt that detection and identification of biological agents should be implemented as two separate activities. Biological detection is defined as measurement of an aerosol cloud which matches some predetermined threat characteristics. Identification is defined as revelation of the genus and species of an organism or the specific type of toxin in a given sample. There are many reasons for making these two tasks distinct. For instance, the technologies involved are dissimilar and the results are operationally used by two different military groups. The information derived from detection is used by field commanders who decide on the best protection plan. To be effective, detection must be carried out rapidly, preferably in minutes so that protective measures could be taken. In contrast the information from identification is used by medical staff who select the best therapeutic treatment schemes. Due to technological constraints, identification schemes using immunological methods are inherently slow, providing results in hours. Advances in coupling biochemical to immunological reactions may speed up the process marginally but often at the expense of sensitivity. The detection-identification scheme would be used later in the system deployed by the Canadian Forces during the Gulf War (see following article). This paper will focus on the development of a BW detection system.

Biological warfare agents are most efficiently disseminated as an aerosol making detection a challenge.

DRE SUFFIELD APPROACH

Before embarking upon a biological detector project, we formulated a few objectives to provide clear direction towards an attainable goal. For example, to study aerosols, we elected to exploit existing technologies, preferably using commercially available instruments, where possible. This was an important consideration because of limited resources. Secondly, we decided to pursue a multiple parameter approach where we would study a number of particle characteristics and environmental aspects to deduce an alarming condition.

Several important lessons can be learned from the US Army's experience of XM19. First, it is well known that different types of biological particles such as pollens and fungal spores occur in the environment, making detection of specific BW agents difficult. Clearly, there is a need for a better understanding of the environment. An obvious approach is to compile a detailed information base of background aerosol characteristics. This knowledge base is essential in formulating a detection and alarming strategy. Second, a detection strategy which measures only one parameter provides inadequate information to eliminate false alarms. Multiple parameters must be assessed to fully describe biological threat situations.

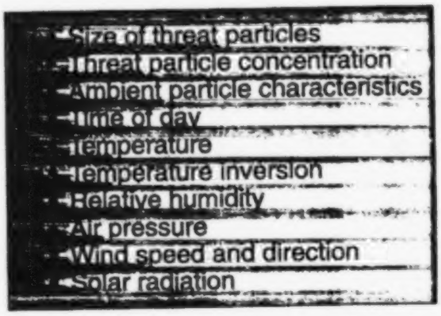


Figure 1: Multiparameter approach examines a number of particle characteristics and environmental and meteorological factors to ascertain potential threat.

The multiple parameter approach emphasizes a new philosophical direction to BW detection (Figure 1). It is consistent with a complex ecology where many biological as well as environmental variables coexist and may interact in different ways. For example, a method is required to distinguish threat agents from a background of other endogenous biological materials such as soil bacteria, fungi and pollens. In addition, the background material may vary with time of day, season or geography. It is well known that most threat agents are susceptible to the ultraviolet rays in the sunlight and under prolonged exposure, may lose their effectiveness. Thus the time of day becomes a critical consideration for launching BW agents. Measuring environmental conditions such as wind speed, direction, relative humidity, temperature, air pressure and time of day could provide important information to assess the threat potential. Ideal conditions for launching BW agents include moderate wind speed, steady wind direction from the most likely sector, temperature inversion and partly cloudy sky (or late afternoon when sun is closer to the horizon) to minimize the effect of solar radiation. On the other hand, all the meteorological data relating to stormy weather would indicate unfavorable conditions.

We aimed to study aerosol characteristics of ambient air in different locations under various climatic conditions. Information thus obtained could be used to determine the changes to these characteristics with respect to time in hours, days and seasons. Since the multiple parameter approach is an open-ended concept, new technologies can be incorporated as they become feasible.

There was an urgent requirement for an aerosol disseminator capable of putting out a reasonable size cloud resembling that of a threat aerosol. Using this device, experiments could be designed to characterize BW threat aerosols. The results of these experiments could be graphically represented in a way which might permit us to visually distinguish the characteristics of threat versus ambient aerosols. If we could train ourselves to visualize these differences then perhaps computer programs could be written to automate this process and also to sound an alarm. This scheme is analogous to the early days of radar when operators were trained to spot enemy aircraft by visually scanning the blips on the radar screen.

With all the sensors providing data in rapid succession, a method was required to process them, and more importantly, to derive an alarming decision. Fortunately, this project evolved at the time when personal computers (PC) became commonly available. Prior to this period, automated data gathering was done (if it was at all possible) with expensive and bulky minicomputers or mainframes. With microcomputers, it became feasible to dedicate a PC to each project station, in this case a detection module.

Graphical representation of particles may enable us to distinguish threat particles... in a scheme analogous to early days of radar when operators were trained to spot enemy aircraft by scanning blips on the screen.

To be effective, detection and alarming systems must operate continuously during deployment. A detection scheme which relies upon wet chemistry as in the XM19 would require replenishment of expendable resources which can become costly. Ultimately, the acceptance and workability of any system must be based on its operational cost. For these reasons, we elected to exploit the measurement of aerosol particle size and concentration using light scattering techniques. This system could operate continuously unattended, collecting particle size data, environmental data and simultaneously performing numerical analysis. Except for electrical power, this method provides continuous operation with no consumable requirements.

Detection capability could be further enhanced by a master-slave networking scheme: a number of detection systems (slaves) would be deployed over a broad geographical area, upwind of the area to be protected, each operating as a self-contained unit. Alarming information would be radio relayed to a master station which then could evaluate information from all the reporting slaves to gauge the depth of potential threat. Such information would be useful to the field commander in assisting him to decide on the most appropriate protective measures. Should an alarm condition occur, sample collectors would be activated automatically at each corresponding detection unit. These would provide aerosol material for subsequent identification analysis using standard immunological techniques.

DETECTION SYSTEM

Aerosol particle measurement using light scattering techniques has been well established and numerous commercial instruments were readily available. However, some instruments were known to produce measurement artifacts, probably associated with light diffraction by small particles or with electronic noise. We examined a number of instruments by analyzing air filtered through Canadian Forces service respirator canisters and found that they produced a residual "signal" which could not be explained. In the early 1980s, TSI (a company in Minneapolis started by aerosol scientists associated with the University of Minnesota) produced an aerosol particle sizer (APS) based on the time of flight principle for monitoring "clean rooms" in the microchip industry. The instrument accurately measured the time a particle took to travel a known distance. From it, the particle aerodynamic diameter could be calculated. Under rigorous testing, the data produced by the APS was found to be free of artifacts and produced unambiguous results. We chose this instrument for sizing aerosol particles.

This was the critical capability that helped us to properly study aerosol characteristics in the laboratory as well as the outdoor environment. By plotting particle number or mass concentrations versus particle size distribution versus time, a three dimensional representation of an aerosol cloud could be visualized (Figure 2). Using a 286-PC, real-time changes in aerosol characteristics could be presented as rapidly as once every second. For the first time, the experimenter could visually correlate direct alterations to experimental aerosols with graphical representations. This enabled us to optically distinguish background aerosols from simulated threat aerosols.

By fine tuning the alarming factors, the system could detect the presence of aerosol particles generated from a single smoking match in a room full of people.

All the lessons learned from these observations were incorporated into a computer program which allowed the user to set certain conditions to define aerosol characteristics e.g. particle count, mass and size distribution. By careful tuning of these conditions, it was possible to distinguish the presence of an "unusual" or threat aerosol against the ambient environ-

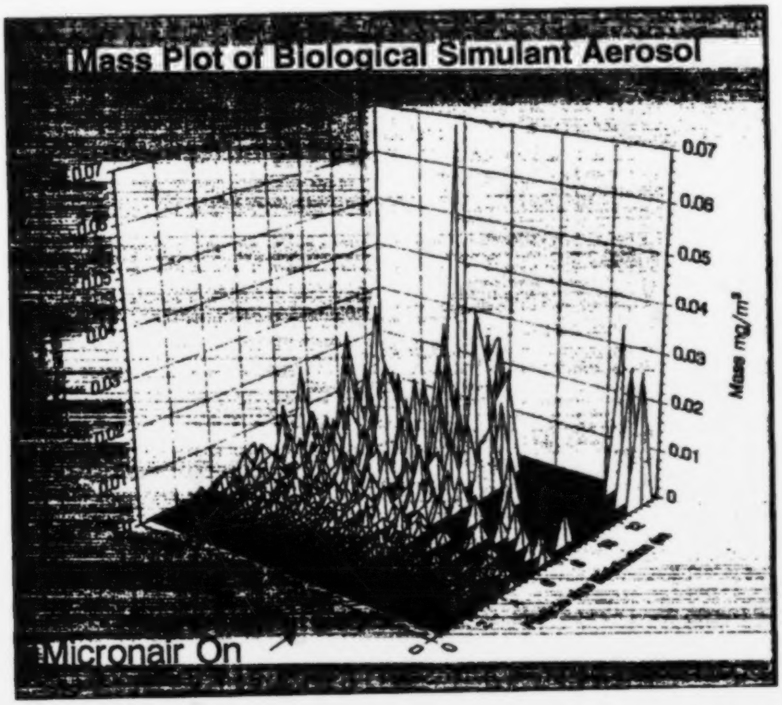


Figure 2
Aerosol measurement using a laser particle sizer. Plot of biological simulant as mass per unit volume vs time can be used to visually distinguish sampled material from ambient particles by their significantly larger mass distribution. Aerosol was disseminated by a Micronair at the indicated time.

mental conditions. Later, the software was refined to compile a running average of the ambient aerosol characteristics to account for naturally occurring slow environmental changes. Other criteria were built into the program to further reduce the incidence of false alarms. For example, a "persistence factor" described how many times the unusual condition should exist before alarming. This capability eliminated spurious "noise" spikes caused by local activities.

Our main objective was to detect an unusual aerosol. An example of an unusual aerosol in the normal living environment would be cigarette smoke or smoke from an extinguished match. Particles of smoke rapidly become invisible on dilution in air. Any good particle detector should be able to measure them as long as their concentration was above that of the background. By fine tuning the various software alarming parameters, the system could detect the presence of aerosol particles generated from a single smoking match in a room full of people. Laboratory and field tests showed that this system could detect the presence of simulant BG aerosols (Figure 2).

Most "threat" particles were in the coarse size range of 3-10 µm and their numbers were much greater than those present in ambient air

AEROSOL SAMPLING

Collection or sampling of the particles in an aerosol is a rapidly evolving technology, spurred on by the needs of the environmental protection industry. Previous field trial experience at DRE Suffield showed that of the two major sampling technologies, water-based and filter-based, the latter was better suited to our needs. Water-based samplers tended to freeze and could not operate reliably at temperatures below 10° C. Aerosol samples collected on filters could be stored dry for later analysis. Finding the commercial instrument was made easier by an Ontario Environment Protection Agency survey which selected the Dichotomous Sampler (DS) as best suited for collecting environmental aerosols. In combination with glass fibre filters as the collecting medium, the DS turned out to be well suited for sampling biological aerosols. As the term "dichotomous" suggests, the instrument collects aerosols in two fractions on two separate filters. The fine fraction consists of particles <2.5 µm and the coarse fraction of >2.5- 15 µm. Coincidentally, large sprayers produce aerosol particles mostly in the coarse range (98%), making the DS an ideal collector of "threat" aerosols.

Initially, the detection equipment consisting of an APS, a 286-PC, environmental sensors and sample collectors were housed in a standard military shelter and trailer. The whole unit, known as the Mobile Aerosol (later Atmospheric) Sampling Unit (MASU) could be towed to different field locations and rapidly deployed for aerosol measurement studies (Figure 3). Anticipating that the MASU may be required to operate in remote and environmentally hostile conditions, it was equipped with air conditioning, power generator and an uninterruptible power supply (UPS) system.

FIELD TRIALS

For field trials, we needed an aerosol sprayer and a BW simulant. A BW simulant is a live organism which has most of the characteristics of the threat agent but does not cause a disease, i.e. nonpathogenic. Anthrax is a disease caused by

Bacillus anthracis, an organism which forms environmentally hardy spores. The simulant for this organism is *Bacillus subtilis subspecies globgii* (BG) which also forms spores. The spores of this organism have useful characteristics such as high viability in storage over a long period (years). Since BG is naturally present in the soil, disseminating an aerosol in the field does not induce any environmental stress. In the laboratory, identifying the organism is simple as it forms an orange colored colony when grown on nutrient agar. We chose BG for our field trials.

To understand an aerosol threat, it is critical that the aerosol characteristics of a simulant closely resemble that of the potential threat. We found that the nature of particulate aerosol characteristics was a function of the disseminating device used to put up the aerosol. These devices could be grouped into three types, depending on their liquid output capacities (high, medium and low). The low and medium output devices were considered unlikely candidates as threat aerosol disseminators due to their inadequate capacity to produce enough material to constitute a threat. Generally, the high output (>1 liter/min. liquid flow) devices as represented by agricultural sprayers produce aerosol particles of a predictable characteristic most resembling threat aerosols. We chose Micronair, an agricultural sprayer with good output efficiency. It uses a spinning cage for liquid droplet breakup and has an integral fan to assist this. The instrument is compact enough to be operated by one person making it very suitable for our purposes. Incidentally, during the Gulf crisis, it was learned that Iraq had the capability of using an agricultural sprayer not unlike the Micronair, to produce biological threat aerosols. Background aerosol data was collected at DRE Suffield and locations off the west coast from Victoria to San Diego. In addition, the area around the airbase at CFB Moose Jaw, Saskatchewan was also examined to study the effect of jet exhaust on ambient aerosol characteristics. We found that atmospheric particle concentration remained fairly stable over many hours within a locality. The naval environment contained significantly fewer particles compared to the terrestrial locations. In either case, the particles present were smaller than 1 µm with little to no contribution from those >2.5-15 µm. (During the Gulf War, we found that data from Qatar and Bahrain also showed a similar size distribution spectra but a higher particle concentration. Aerosol particles

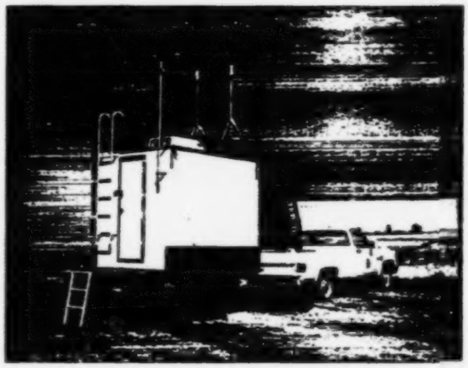
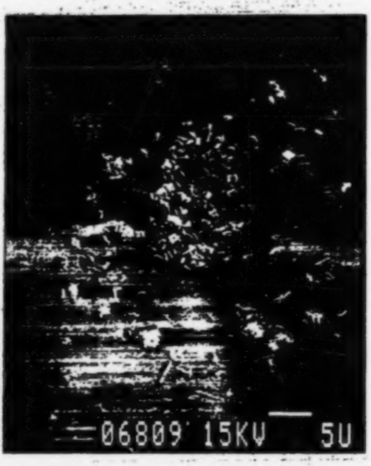


Figure 3.
Field trials with BG simulant. A MASD unit is stationed downwind from release point of simulants. The system can detect low concentrations of biological aerosol and then collect samples for later analysis.

Sticky Aerosols:



Clumping properties of biological particles.

Most microorganisms produce extracellular polysaccharides called levans as a byproduct of cell metabolism. Organisms associated with the open air environment use levan as a protective coating to filter out harmful UV light, and protect against dessication and mild chemical insults. Apart from serving as a filter, levans are glue-like substances that help bind cells to each other or other particulate objects. These cells tend to aggregate into clumps, thus ensuring survival of a few individuals enclosed within. Thus, in nature, microorganisms survive better from environmental damage if they evolved the ability to produce levan. In contrast, organisms whose habitat is in the intestines have generally no capability to produce levans. Hence, they are more fragile when exposed to open air and have been known to die rapidly.

Levans have been recognised as a potentially useful bioindustrial product, similar to chemical polymers like plastics and nylon. This biopolymer is viewed as a potential biodegradable product suitable for packaging or as a filler in the food industry. Various bacteria have been exploited for production of levan and *Bacillus subtilis*, the simulant used in the work described here, is an actively utilised industrial producer.

associated with human activities were easily identifiable as transient spikes. These observations confirmed previous studies and, therefore, did not require changes to the detection strategy.)

A version of the detection system was used during the Gulf War to warn against possible biological warfare attacks. The system performed as expected and did not cause false alarms.

In contrast, we found significantly different aerosol characteristics from "threat" aerosols generated from the Micronair sprayer. Specifically, most "threat" particles were in the coarse size range of 3-10 µm and their numbers were much greater than those present in ambient air. This observation was supplemented by measurements of collected samples using a scanning electron microscope. Studies of particles collected from a Micronair sprayer revealed that these 3-10 µm particles consisted of aggregates of individual spores (0.6-1 µm in diameter). Each particle contained from one hundred to several thousand spores (This tendency of biological particles to clump together is believed to be a survival strategy. See box on p 16). This information was critical for optimizing the alarming algorithm. Along with testing for concentration, the alarming condition also included a test for the presence of this "threat" size group.

This was a new and an important finding. Previous to this discovery, it was thought that threat aerosols exist predominantly in the 1 µm region, this being the average size of bacterial cells and spores. This misconception arose because most researchers had used laboratory aerosol generators specially designed to produce monodispersed 1 µm particles. However, these generators were only capable of small output (<1 ml/min. liquid flow) and thus were not suitable for field trials. Relatively crude large volume sprayers had been used in the field trials but their output particle size was not well characterized.

The MASU system was used in many trials including the Laser Cloud Mapper (a laser based device developed at DRE Valcartier to detect smoke and other aerosol particles) trials carried out at DRE Suffield as well as at DRE Valcartier. In this case, MASU functioned as reference aerosol sampler and performed well. Results from these trials advanced our understanding of aerosol cloud transport characteristics and also of light scattering by particle aggregates. The success of the MASU led to building five additional systems for large scale field trials. To enhance the detection capability, we used radio modems to link the units in a master-slave configuration

During the Gulf conflict, it was known that biological warfare agents had been stockpiled by Iraq and might be used against Allied Forces. Of special interest to us was the possibility that these agents could be disseminated by an agricultural sprayer, with output particle characteristics similar to that of the Micronair. The implication was that the experience gained from field trials with the Micronair was applicable to fine tune the detection and alarming algorithm used at the Gulf. A MASU could provide a capability for prompt warning to alert the Canadian troops of the presence of a potential aerosol threat and thus facilitate the timely use of appropriate protective equipment. A full account of development and deployment of ruggedized mobile aerosol sampling and identification systems based on the accumulated scientific

Fluorescence of biological particles

Flow cytometry (FC), a tool originally designed for mammalian cell studies, can be used to characterise micron size particles such as bacteria and spores. A commercial instrument optimised for microorganisms has been used to measure light scattering and fluorescent signals emitted from a single spore. The results show that exciting a spore with 365 nm light can provide information related to some particle characteristics. There is indirect evidence to suggest that the fluorescence signal is related to intra-spore biomolecules. Fluorescence could be a useful measurement for rapid non-specific detection of biological agents, functioning as a cueing system that can quantify and qualify collected particles as biological or non-biological. This detection scheme could help reduce potential false alarms in particle analysis systems as well as offering the distinct advantage of not requiring prerequisite antigenic knowledge of the threat agents. In addition, the technique requires no expenditure of costly reagents to operate and thus is amenable to incorporation into continuous monitoring operations. It is also demonstrated that FC may be capable of identifying BW agents if specific antibodies are available. It is envisioned that this function can be activated after fluorescence measurements indicate a potential biological threat is present. Thus antibody based reactions could be employed as a secondary confirmation step in the detection scheme.

knowledge of aerosol detection and agent identification is provided in a following article.

INTERNATIONAL COLLABORATIONS

In the early 1980s, an international (UK, US, CA) action group was formed to explore aerosol technology pertaining to military defence. Specifically, it was to define the nature of chemical and biological (CB) aerosol threats and to study all related aspects, preferably avoiding unnecessary duplication of efforts between various participants. Most of the ideas discussed here were shared in this forum and were adopted by the other members. The three countries agreed that light scattering technology e.g. use of lasers to measure size distribution or to interrogate biological content (see box on p 17) should be the primary means to characterize a threat aerosol. Monitoring background aerosol to acquire a database became a common doctrine. There was also agreement with the Canadian proposal that threat aerosols are most likely to be within the size range 3-10 µm.

CONCLUSIONS

The science of biological detection is truly a multidisciplinary endeavour. Technologies from diverse fields like physics, fluid dynamics, microbiology, biochemistry, microcomputer hardware and software interfacing are routinely called upon to solve problems. In several instances, we had to encroach on unfamiliar disciplines to achieve our goals. As a result, we pioneered a number approaches in the field of biological detection: for example, the use of Apple II and PCs for real-time data gathering and graphical display of results and the use of glass fibre filters for biological aerosol collection.

We have developed a detection and alarm system to warn against biological threat agents. It has proved successful in field trials and a version of the system was successfully deployed during the Gulf War. Future enhancement in BW detection will include interrogating biological character of the aerosols to distinguish them from non biological aerosols like smoke particles. Recent studies by the author and his colleagues indicate that fluorescence exhibited by many biological particles (see box on p 17) may be used, in addition to particle density and size measurement techniques described here, to enhance the detection and identification of BW threats. Future research will continue to utilize the MASU as the basic platform for exploring new generations of detection systems. Using modern instruments, we anticipate that an automated identification system will be integrated within the space of the MASU.

Suggested Readings

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Ho, J., B.T.N. Evans and G. Roy. Laser detection and mapping of biological simulants III. Dichotomous sampler measurements of aerosol concentrations as related to LIDAR signals (U). Suffield Report No. 532. (1990) (Unclassified)

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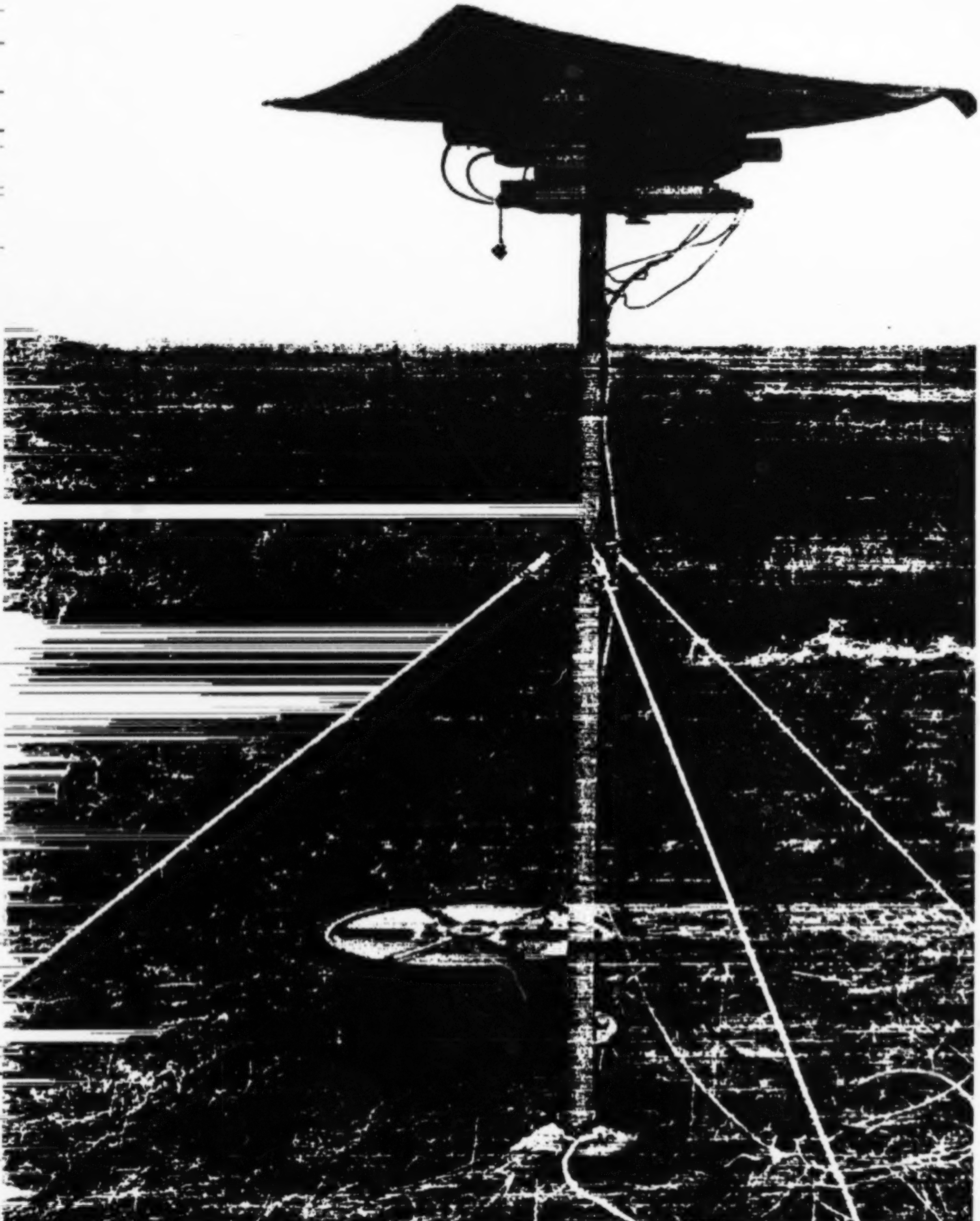
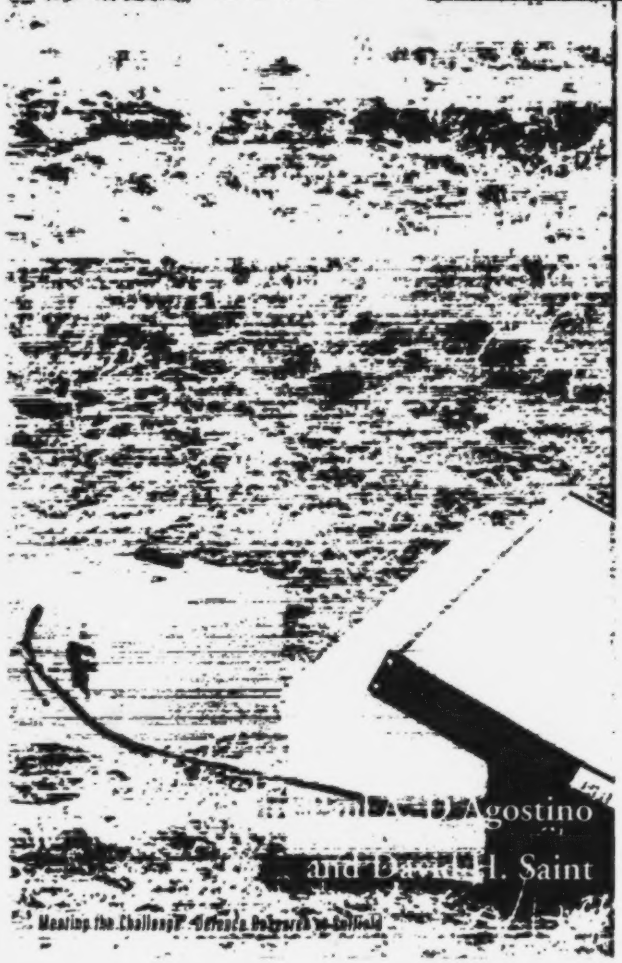


REMOTE DETECTION OF CHEMICAL WARFARE AGENTS

development of a network of monitors to meet Persian Gulf War requirements



[illegible] Agostino
and David H. Saint

Evolution of Chemical Weapons

Chemical warfare agents are toxic chemicals that have been defined by the United Nations Chemical Weapons Convention as "any chemical which, through its chemical effect on living processes, may cause death, temporary loss of performance, or permanent injury to people and animals". Poisonous or toxic compounds have been utilized in an effort to gain military superiority throughout history but it is only during the past century that chemical warfare agents have been produced and used on a large scale. Tear gas grenades were used in 1914 by the French at the outbreak of the First World War, but it was not until the Germans used chlorine near Ypres in 1915 that the world entered the modern era of chemical warfare. Other chemical warfare agents such as phosgene and mustard were weaponized during the First World War and were used by both sides throughout the conflict. The use and development of chemical warfare agents continued following the First World War with mustard being used by the Italians against the Abyssinians in Ethiopia during the 1936-1937 War.

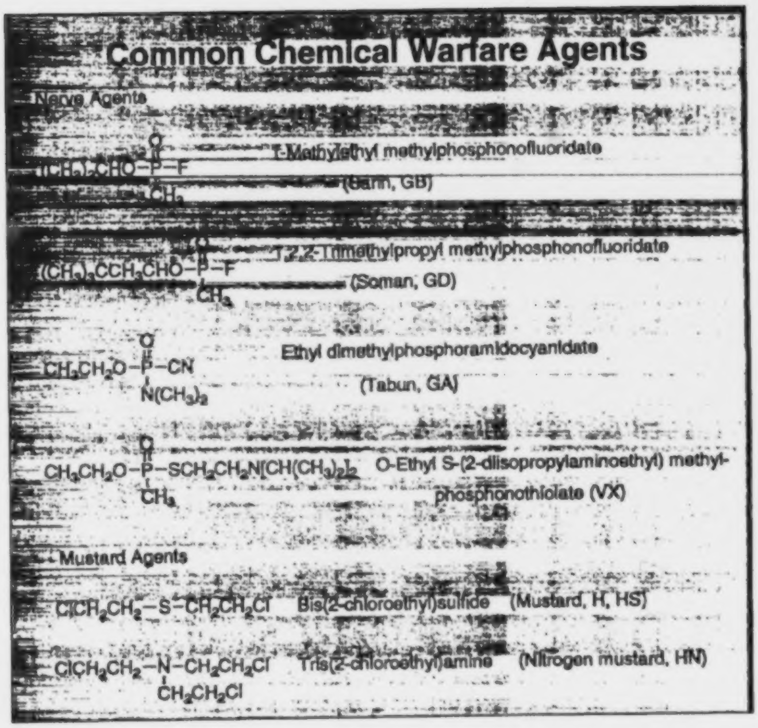

Common Chemical Warfare Agents
Nerve Agents
(CH3)2CHO-P(O)(CH3)-F
1-Methylethyl methylphosphonofluoridate (Sarin, GB)
(CH3)3CCH3CHO-P(O)(CH3)-F
1,2,2-Trimethylpropyl methylphosphonofluoridate (Soman, GD)
CH3CH2O-P(O)(N(CH3)2)-CN
Ethyl dimethylphosphoramidocyanidate (Tabun, GA)
CH3CH2O-P(O)(CH3)-SCH2CH2N[CH(CH3)2]2
O-Ethyl S-(2-diisopropylaminoethyl) methylphosphonothiolate (VX)
Mustard Agents
ClCH2CH2-S-CH2CH2Cl
Bis(2-chloroethyl)sulfide (Mustard, H, HS)
ClCH2CH2-N(CH2CH2Cl)-CH2CH2Cl
Tris(2-chloroethyl)amine (Nitrogen mustard, HN)

Figure 1: The six chemical warfare agents detected by the Chemical Agent Monitor.

■

DRE Suffield was tasked to develop and produce, within a two month period, a chemical warfare agent detection system...

■

Prior to the Second World War, the Germans discovered and produced the first nerve agent, tabun. Nerve agents were weaponized by the Germans but neither side made use of their chemical weapons stocks. More effective nerve agents, such as VX, were developed in the 1950's, mustard was used in the Yemen War (1963-1967) and allegations of chemical warfare agent use were reported in South East Asian conflicts. Currently, the most significant chemical warfare agents in terms of military capacity and past use are the nerve and mustard agents (Figure 1). Both nerve and mustard agents were used extensively by Iraq in the 1980's war between Iran and Iraq, and were considered a serious threat to Canadian and other United Nations armed forces personnel during their actions against Iraq in 1990-1991.

Iraq's Chemical Weapons

(from: A Briefing Book on Chemical Weapons ISBN 91-7056-085-4)

Type	Calibre	Range (km)	Charge (kg)	Agent Type
Bomb	LD 250	–	50	Mustard
Missile Warhead	Al Hussein	600	150	Sarin
Artillery Rockets	122 mm	20 to 35	7	Sarin
Artillery	155 mm	10 to 30	3	Mustard

How chemical weapons work.

Nerve agents are extremely toxic organophosphorus compounds that can enter the human body by inhalation or by absorption through the skin. These compounds exert their toxic effect rapidly by reacting irreversibly with acetylcholinesterase, the enzyme responsible for the breaking down acetylcholine. The resultant accumulation of acetylcholine causes continual stimulation of the human body's nervous system which results in convulsions, loss of consciousness and eventual death.

Mustard or "blister" agents affect the skin, eyes, lungs and gastro-intestinal tracts of the human body. The symptoms of mustard poisoning are delayed for several hours after exposure, at which time the victim may experience loss of sight, the formation of skin blisters, nausea, respiratory difficulty, vomiting and diarrhoea. Victims require long recuperation times in medical care and generally die from complications related to lung damage caused by the mustard.

The CADS Mission

Canadian Forces deployed to the Persian Gulf were stationed at fixed site installations in Bahrain and Qatar. The headquarters in Bahrain and airbase in Qatar were both at risk to downwind drift of chemical or biological warfare agents by the prevailing winds. The Canadian Forces had on inventory the hand-held Chemical Agent Monitor (CAM) which could be used for real-time monitoring of mustard and nerve vapours in chemically contaminated environments, but did not have a detection system that could be deployed upwind of the sites for the remote detection of chemical warfare agents.

DRE Suffield was tasked to develop and produce, within a two month period, a chemical warfare agent detection system, based on the CAM, that would provide early warning of an off-site chemical incident. Canadian Forces personnel, warned by this system, would then be able to take appropriate chemical protective action, including the donning of protective respirators and charcoal impregnated suits, to minimize chemical exposure.

The CADS Project

DRE Suffield was in the process of developing a monitoring network of CAMs in support of Project Swiftsure, a project that included the incineration of Suffield Experimental Range chemical warfare agent stocks and waste. CAMs were to be linked by cable over short distances (up to 100 metres) to a central computer where the results of each CAM measurement would be displayed on a computer terminal. An alarm would be sounded in the event of an accidental release of chemical warfare agent within the Project Swiftsure incineration complex. This general concept of operation seemed to meet the Canadian Forces threat assessment in the Persian Gulf with two notable exceptions. The military requested the capability to place the CAMs at distances of up to 1000 metres, to give sufficient warning time for personnel, and required ruggedization of the system.

DRE Suffield, in the fall of 1990, responded immediately by developing and purchasing the required hardware and by modifying the Project Swiftsure software for ease of use by military personnel. Within four weeks DRE Suffield developed, assembled and field tested the three Chemical Agent Detection Systems (CADS) required for deployment in the Persian Gulf in support of Canadian Forces operations. During the ensuing two weeks two DRE Suffield personnel were airlifted with the equipment to the Persian Gulf where it was installed and the end users were given the training required for its operation. This unique remote detection capability was shared with our allies, with a fourth CADS being installed by DRE Suffield personnel in January 1991 at an American Air Force base adjacent to the Canadian compound in Qatar.

How the CAM Detects Chemical Warfare Agents

The CAM unit draws air continuously across a heated silicon membrane which preferentially allows chemical warfare agents to pass through into the analysis portion of the CAM. The chemical warfare agents are carried by an air flow into the ionization section, where a weak emitter of beta particles ionizes air molecules. Ion-molecule reactions result in the formation of a population of positively and negatively charged air complex ions (reactant ions) of the following general structure.

Positive Reactant Ions: $[H^+(N_2)_x(H_2O)_y]$

Negative Reactant Ions: $[(O_2)(N_2)_x(H_2O)_y]^-$

Chemical warfare agents, at the parts-per-million level in air, ionize if they come into contact with reactant ions with a lower affinity for charge. Charge transfer to the chemical warfare agent takes place and charged chemical warfare agent complexes form (product ions). The generated reactant and product ions are then removed from this section by applying an electrical field. Nerve agents, which form positive product ions, are drawn out with one polarity while mustard agents, which form negative product ions, are drawn out with the opposite polarity.

Nerve Agent Detection:

$$\underset{\text{Reactant ion}}{[H^+(N_2)_x(H_2O)_y]} + \underset{\text{Nerve agent}}{G} \longrightarrow \underset{\text{Product ion}}{[GH^+(N_2)_x(H_2O)_y]}$$

At higher nerve agent concentrations the shown product ion will react with another nerve agent molecule and the dimer, $[G_2H^+(N_2)_x(H_2O)_y]$, will predominate.

Mustard Agent Detection:

$$\underset{\text{Reactant ion}}{[(O_2)(N_2)_x(H_2O)_y]^-} + \underset{\text{Mustard agent}}{H} \longrightarrow \underset{\text{Product ion}}{H[(O_2)(N_2)_x(H_2O)_y]^-}$$

All ions are then gated into a 5 cm drift tube with an electric field strength of 250 volts/cm, where each of the ions drifts according to its mobility. In general the reactant ions are detected at the collector electrode prior to arrival of the product ions. Different chemical warfare agent product ions drift with differing mobilities and identification of the type of chemical warfare agent is based on the mobility of the formed product ion relative to the reactant ion.

CADS was the first network of remote chemical agents detectors deployed in a military setting and provided the

Canadian Forces with the advantage of being able to perform their duties without the added heat stress caused by continuously wearing individual protective clothing. This was a considerable advantage to the Canadian Forces working in the hot, humid conditions of the Persian Gulf.

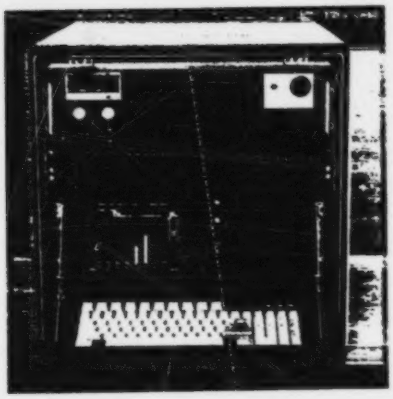


Figure 2 CADS central control unit

CADS Central Control Unit

Each CADS was controlled by a central control unit capable of monitoring four sampling stations positioned at distances up to 1000 metres from the central control unit. Figure 2 illustrates the central control station developed at DRE Suffield. It consists of a ruggedized computer, a 30 volt 10 amp power supply, a switchable audio alarm, a power bar and an interface panel all housed in a shock resistant aluminum case.

The 30 volt 10 amp power supply can drive four sampling stations from the central control station. Under these conditions, the interface module at each of the four sampling stations provides the required 5 volts DC to the CAM units, thus negating the need for battery operation. Each sampling station has five spring connectors located on the interface panel for serial data transmission and for the provision of power to the CAM units. Serial data from each CAM goes to an interface card housed within the computer where the identity of the chemical warfare agent and threat level is decoded.

A power bar and interface panel have been mounted at the rear of the case. The power bar has built in surge suppression and both the computer and the internal power supply receive their power from the power bar. Continuous operation of the system during a power failure is possible for about 30 minutes using an external 110 volts AC power supply, connected to operate uninterruptedly. If power is interrupted to CAM units a message indicating that CAM units are off will appear on the monitor screen.

The CADS has two alarms, one housed within the computer, and the other mounted opposite the power supply. The internal alarm utilizes the computer's speaker and produces a low unobtrusive sound that may not be turned off. The second alarm produces a loud high pitched sound upon alarming that may be switched off if desired.

> ■
>
> **The user observes up to an 8 bar response, ..., and an audio signal if the response exceeds 3 bars.**
>
> ■

CADS Operation

An introductory page, indicating the capabilities of the CADS, appears on the computer screen immediately after providing power to the central control station. Real time monitoring of the four sampling stations begins by hitting any key on the keyboard. This real time display, illustrated in Figure 2, indicates the sampling station number on the x axis and the level of threat on the y axis. Mode of operation of the CAM units at each sampling station is indicated by the presence of a letter (nerve (G) or mustard (H)) above the sampling station number and the colour of the bars (yellow = H agent and red = G agent).

Should a chemical warfare agent be detected at one or more of the sampling stations the user observes up to an 8 bar response, identical to the CAM display, and an audio signal if the response exceeds 3 bars. The identity of the chemical warfare agent detected appears as a two letter code in a window in the upper right hand corner of the display. The following chemical warfare agents may be detected in the G- and H-modes of the CAM.

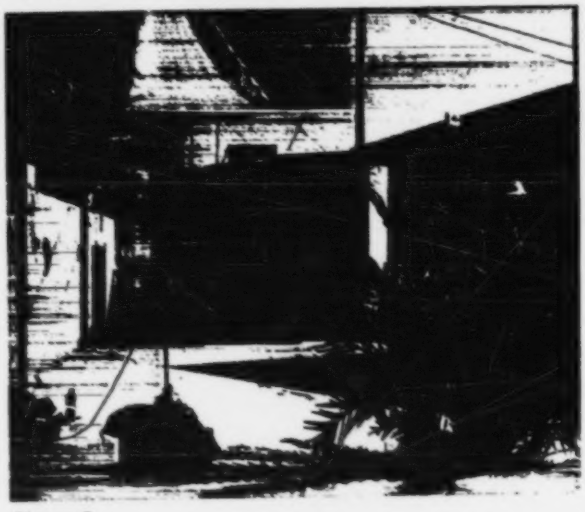


Figure 3
CADS sampling station at Canada Dry 1 (Qatar).

G-Mode (nerve agents)	H-Mode (mustard agents)
GB: Sarin	HS: Sulfur Mustard
GD: Soman	HN: Nitrogen Mustard
GA: Tabun	
VX: VX	

CADS Sampling Station

A sampling station had to be developed that would hold the CAMs and interface in a stable manner and provide shade from the sun for the CAMs. Each sampling station was connected by 7 conductor 14 gauge cable to the computer and holds two CAM units to facilitate simultaneous real time monitoring of both mustard and nerve agent vapours. The CAMs and the DRE Suffield developed interface module are located on the sampling pole and a sun shade was provided to reduce the surface temperature of the CAMs. Sampling stations were erected as illustrated in Figure 3 with the two CAMs being mounted on an adjustable bracket using velcro straps. The interface module, connected to the CAM units by a cable, regulates power to the CAM units and transmits serial data from the CAM units to the central control unit.

> ■
>
> **The system could be improved by providing alternate means of data transmission, by reducing the package size, and by incorporating less expensive computing technology.**
>
> ■

Development of CADS II

The first CADS systems were developed, assembled and field tested at DRE Suffield on a very tight schedule that did not allow incorporation of technical improvements that would enhance the reliability, maintainability and versatility of use of the system. Following deployment, it was apparent that the system could be improved by providing alternate means of data transmission, by reducing the package size, and by incorporating less expensive computing technology. In addition a requirement for the use of CADS to support maritime operations was also identified. These factors led to the joint development and commercial production of a second generation of CADS, designated CADS II, by Scientific Instrumentation Limited (Saskatoon).

The CADS II central control unit, illustrated in Figure 4, is a more rugged, portable unit incorporating a single board computer running EPROM embedded applications software. The power supply is more versatile and is capable of operating from 90 to 130 and 200 to 260 volts AC (50/60 Hz) or with a 24 volts DC supply. An internal battery allows uninterrupted operation in the event of a power failure.

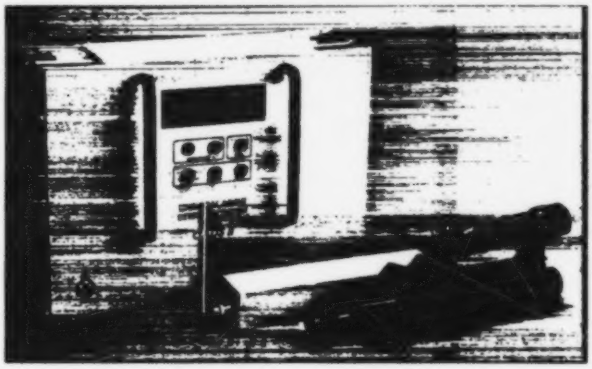


Figure 4
CADS II central control unit (background), radio frequency transceiver (mid-ground) and Chemical Agent Monitor (foreground).

CADS II also has the ability to perform three additional functions, recognized as deficiencies in the original CADS design, through the use of a three button keypad located below the alarm on/off and display illumination button. The operator of the central control unit has the ability to turn power on and off to any of the sampling stations, set the threshold level (number of bars) for alarming of both G- and H-mode CAM

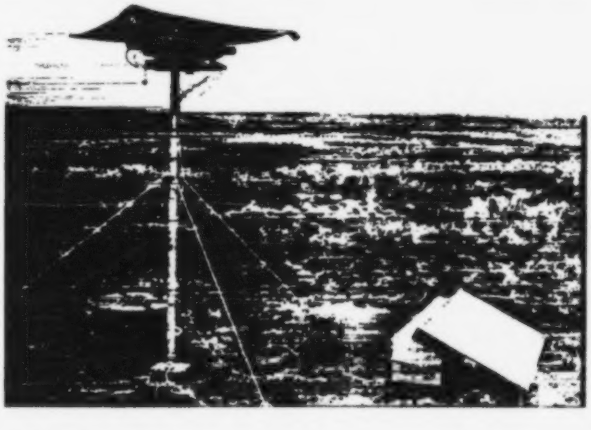


Figure 5
CADS II sampling station operating on 1500 metres of single twisted pair for serial data transmission. The solar panel is leaning against the storage case for the sampling station and the rechargeable battery lies between the mounting pole and the solar panel.

units in the system and initialize new or existing sampling stations. Sampling station capacity was increased to eight stations, each containing two CAM units in a manner similar to the original design.

CADS II Operation

The central control unit undergoes a short initialization procedure followed by display of real time monitoring data. Real time monitoring of the eight sampling stations is displayed on a liquid crystal screen with sampling station number on the y axis and threat level, in bars, on the x axis. The mode of operation of each CAM is indicated by the presence of a letter (G for nerve agent detection and H for mustard agent detection) opposite the station number. Should chemical warfare agent be detected at one or more of the sampling stations one observes up to an 8 bar response, identical to the CAM display. The identity of the chemical warfare agent appears as a two letter code in manner identical to the original CADS following the bar display.

Problems including CAM failures or communication errors are indicated in the liquid crystal display region used for CAM bar response. Messages such as backup battery and alarm status appear at the far right of the display and do not interfere with the real time bar display of the 16 CAM units.

> **Sampling stations may now be connected to the CADS II in any combination of the following three possible configurations.**

Sampling Station Improvements

The original CADS could only be connected by heavy cable to the central control unit. This configuration, while useful for long term fixed site operation does not permit rapid deployment and re-deployment of CADS. For this reason two additional optional sampling station configurations were developed. Sampling stations may now be connected to the CADS II in any combination of the following three possible configurations:

i) with up to 1000 metres of heavy cable in a manner identical to the original CADS. Power is supplied to the CAM units at the sampling stations from the central control unit.

ii) with up to 3000 metres of light single twisted pair for serial data transmission. Power to the CAM units at the sampling station in this configuration is provided by a solar panel with a rechargeable battery backup.

iii) the sampling station may communicate serial data using radio frequency transmission over distances up to 4000 metres. Power to the CAM units and the radio transmitter is provided by a solar panel with a rechargeable battery backup.

The sampling station pole now telescopes to decrease the bulk of each station and a bracket was mounted on the pole below a lower profile sun shade to permit mounting of the CAMs, the interface module and the optional radio frequency transceiver. The complete sampling station, excluding CAM units, is stored in a shipping case, half the size of the original design.

CADS II Deployment

CADS II would have been deployed to the Persian Gulf for use by Canadian Forces in place of CADS systems in Bahrain and Qatar if the ground war had continued. Fortunately the ground war was shortlived and there was no need to ship this equipment into theatre. However the successful use of a network of detectors did not go unnoticed by our United Nations allies. Following the war the United Nations requested that Canada provide CADS II systems during an United Nation Special Commission (UNSCOM) mission tasked with the destruction of leaking Iraqi rockets in Khamisiyah, Iraq. CADS II was set up by DRE Suffield staff at the weapons storage site where it performed perimeter monitoring and personnel safety roles over a four week period in early 1992 (Figure 6).

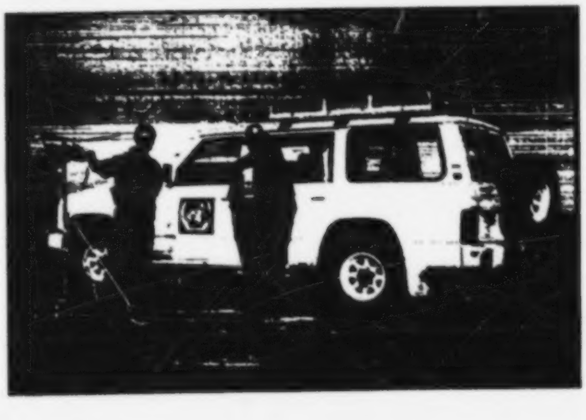


Figure 6:
CADS II sampling station deployed by DRE Suffield personnel during UNSCOM destruction of Iraqi chemical rockets.

■
The United Nations requested that Canada provide CADS II systems during an United Nation Special Commission (UNSCOM) mission.
■

At the same time a maritime version was deployed on the HMCS Restigouche for patrolling in the Red Sea in support of United Nations sanctions against Iraq. The central control unit used in the maritime version was housed in the bridge and was identical to the land based version, with the CAMs being linked to the central control unit by cable. However there was concern over the operation of CAMs in a salt spray environment. A maritime sampling station protective enclosure was developed to seal the CAMs and the interface module from salt spray. Figure 7 illustrates a CADS II maritime enclosure installed aboard the HMCS Restigouche prior to patrolling. CADS II systems are currently stored in a ready state at DRE Suffield for future use by Canadian Forces personnel deployed to regions where there is risk of chemical warfare agent use.

Summary

DRES successfully developed, assembled and field tested four Chemical Agent Detection Systems (CADS) for deployment in the Persian Gulf in support of Canadian Forces operations. These remote detection systems were located at the Qatar and Bahrain Canadian Forces sites and an adjacent American Air Force base in Qatar where they performed as chemical warfare agent alarms for the duration of the Persian Gulf War.

The second generation CADS II system, now commercially available, is smaller, more versatile, much less expensive and more rugged than the original CADS design. CADS II uses the well proven, commercially available Chemical Agent Monitor to detect chemical warfare agent vapours. Operation of the CADS II system remains extremely simple, requiring a skill level similar to operation of a Chemical Agent Monitor. This fact coupled with its low unit cost and unsurpassed remote sampling capabilities makes this detection system an attractive option for use by both military and United Nations personnel interested in remotely detecting chemical warfare agent vapours.

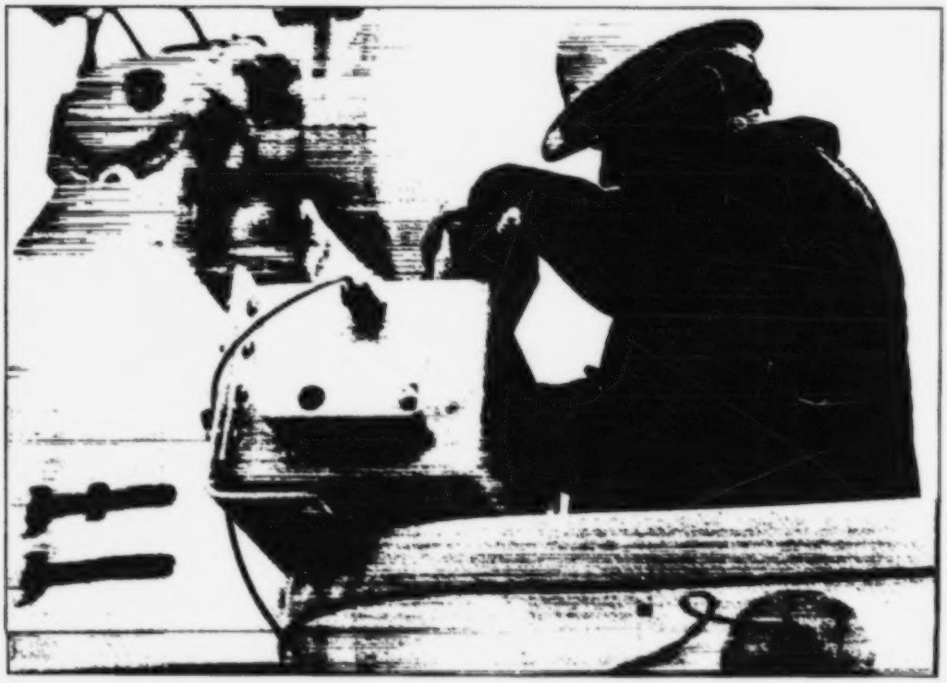


Figure 7
CADS II maritime enclosure aboard the HMCS Restigouche prior to patrolling in the Red Sea in support of United Nations sanctions against Iraq.

IRAQ
JORDAN
D E S E R T
Al Jafr
Jabal Rāf
An Nafūd
Jabal Shammar
Al Wajh
Ra's Abū Madd
Yanbu' al Bahr

Bandah
Iskandariya
Musayyib
STRATEGIC PIPELINE
Samawah
An Nas
Jalibah
Ar Rumaylah
(Basra)
Umm Qasr
Hijārah
KUWAIT
Ad Dibdibah
Ash Shuwaykh
240+
Ra's al Kha
Hafar al Batin
Al Qaysumah
KING KHALID MILITARY CITY
NATIONAL
the auspices of
ited Nations, at
uest of Kuwait's
nment-in-exile, 24
es sent armed
in the Persian
response to
ggression.
408+
Ad Dahna
AR RIYAD
(RIYADH)
PIPELINE
SAUDI ARABIA

[redacted]

IELD DETECTION & IDENTIFICATION OF BIOLOGICAL WARFARE AGENTS

Full protection of Canadian Forces during the Gulf Crisis required the capability for the rapid detection and identification of biological warfare agents

The invasion of Kuwait by Iraqi forces in August 1990 precipitated a chain of events that ultimately led to the Gulf War. This short but intense conflict included several months of build-up of the forces opposed to the invasion. The Allied Forces consisted of both Western and Arab nations including the United States, the United Kingdom, France, Canada, Saudi Arabia, Bahrain, Qatar and Syria, among others. The Allied Forces operated under the mandate of a number of United Nations resolutions.

The Canadian Joint Headquarters (JHQ) was located at Manamah (Al Manamah), Bahrain and was the commanding unit for the Canadian Forces (CF) deployed as part of OPERATION FRICTION, the code name given to the Canadian operation. The Canadian warships (HMCS Athabaskan, HMCS Terra Nova and HMCS Protecteur) operated in the Arabian (Persian) Gulf. During the blockade phase preceding the start of hostilities, the Canadian ships were involved in a large number of hailings and boardings; during the war itself the ships were involved both in continuing the enforcement of the blockade as well as other functions supporting Allied Forces air and ground operations.

The Canadian Air Force operated from Doha (Ad Dawhah), Qatar, and had the mission, in concert with Allied Air Forces, of establishing and maintaining air-to-air superiority. During the land war, the Canadian aircraft began air-to-ground missions. The Canadian Field Hospital was located near Al Qaysumah in northern Saudi Arabia. The hospital was in deployment when the ground war began with part of its capability being in-theatre. A field hospital is geared for re-deployment and could be re-located rapidly as warranted by tactical circumstances. Due to the shortness of the ground war, this proved to be unnecessary.

OPERATION FRICTION
1991
TURKEY
SYRIA
IRAQ
IRAN
EGYPT
SAUDI ARABIA
OMAN
YEMEN
SUDAN

Map of the Theatre of Operations-Canadian Forces Operations Middle East (CANFORME) were conducted from Al Manamah (Bahrain), Ad Dawhah (Doha, Qatar), and Al Qaysumah (Saudi Arabia) and included, respectively, the Canadian Joint Headquarters (JHQ), the Canadian Air Tactical Group Middle East (CATGME) and the Canadian Field Hospital.

Of particular concern in this operation was the threat of the overt or covert use of chemical and biological weapons. Intelligence assessments and Iraqi claims combined to create an environment in which the possibility of the use of such weapons had to be considered (Iraq had previously used chemical weapons in its war with Iran). This situation created a number of urgent requirements for identifying, developing and fielding equipment that could be utilized in protecting and decontaminating troops against chemical and biological threats.

While operations in an environment with chemical warfare (CW) agent threats had, on the whole, been previously addressed by the operational doctrine and equipment of the CF and Allied Forces, the same was not as true for operations in an environment with biological warfare (BW) agent threats. At the start of the Gulf Crisis, field BW agent detection and identification equipment was not available to the CF (or to the Allied Forces), and, as importantly, the operating doctrine for such an environment was not well established.

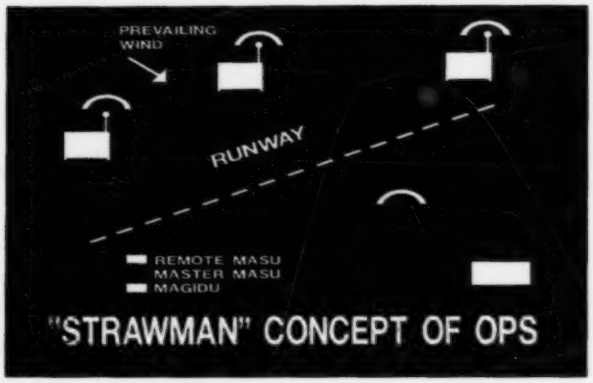
An essential element in operating effectively in such an environment is the capability for timely detection and identification of the agents. The inability to do this for BW agents, in particular, resulted in a high priority effort at the Defence Research Establishment Suffield (DRE Suffield) to rapidly develop a fieldable BW threat detection and identification capability for the CF. It is noted that for many biological hazards, early detection is critical to effective medical treatment and a high survival rate.

The research program in the Defence Sciences Division (DSD) of DRE Suffield has developed a number of techniques for providing early warning of the presence of any type of agent that is being encountered. The Gulf Crisis resulted in an urgent requirement to take the most promising of these techniques and package them into ruggedized, user-friendly systems that were suitable for rapid deployment and use by the CF. These system design and integration efforts required extensive support from the Defence Technologies Division (DTD). Two of the projects whose design, system integration and deployment was led by DTD included the Chemical Agent Detection System (CADS, see the companion paper "Remote Detection of Chemical Warfare Agents" [D'Agostino and Saint]) and field BW agent detection and identification units. The latter consisted of detector and sampling elements that are co-located in one or more Mobile Atmospheric Sampling Units (MASU's) and an agent identification capability that is located in a ruggedized field portable laboratory referred to as the Mobile Agent Identification Unit (MAGIDU). Together, one MAGIDU and one or more MASU's form a Mobile Atmospheric Sampling and Identification Facility (MASIF).

PROTOTYPING AND INTEGRATION

The project started in early October 1990 after the decision had been taken to develop a fieldable system and involved, at various times, virtually all sections at DRE Suffield as well as Canadian Forces Base Suffield and a number of contractors.

An intense design, prototyping and integration effort was required at DRE Suffield before MASIF would be ready for deployment. The project started in early October 1990 after the decision had been taken to develop a fieldable system and involved, at various times, virtually all sections at DRE Suffield as well as Canadian Forces Base Suffield and a number of contractors. The objective was to take the scientific techniques



"Strawman" Concept of Operations around which the DRE Suffield teams developed MASIF.

developed in DSD at DRE Suffield and package them into a system that could be deployed into the field environment of the Middle East. It involved the engineering integration of many subsystems, and was led by staff of the DTD whose R&D activities had provided extensive experience in the proof-of-concept development and deployment of a variety of military systems.

Project teams were formed to address a number of critical issues and provide input to the engineering team responsible for the prototyping and integration of the MASU and MAGIDU. Needless to say, the total commitment of all of the technical and management teams was essential to overcoming a number of critical schedule and technical obstacles. Extensive support from a number of DRE Suffield and CFB Suffield support groups was also critical to the success of the effort. The main objectives of this phase were as follows:

- To take the existing laboratory techniques, evolve new ones as required and integrate them into ruggedized, field deployable systems.
- To train CF personnel in the operation and routine maintenance of the systems.
- To assist the CF in developing a concept of operations and appropriate Standard Operating Procedures; and
- To provide technical support to the CF during the deployment and initial operation of the systems.

Five ruggedized MASU's and one MAGIDU were designed and integrated at DRE Suffield; some subsystems were built under contract (ADGA Systems International, Atlantis Aerospace, ATS Aerospace, Boeing Canada, Intercontinental Truck Body and others). All of these, except for one MASU, were deployed with CF units operating in the Middle East. One MASU remained at DRE Suffield as a functioning spare and was also available for ongoing system development and testing.

It is noted that the initial portion of this work was focused on MASU; the requirement for a field-deployable MAGIDU was recognized part way through the work, and necessitated the formation of separate teams to address the MAGIDU design, prototyping and integration. Intense effort was also required by DSD scientists and technicians in developing a test suitable for rapid, field identification of BW agents.

The MASU element of the system provides for the detection of a possible BW agent dispersed as an aerosol. MASU can be deployed as a single, stand-alone unit, or in an array of units that consist of a master unit and one or more remotes. The detector, meteorological and other system status data is passed between the remote and master units utilizing a UHF radio data link (see "Strawman" Concept of Operations).

Field Deployment Concept

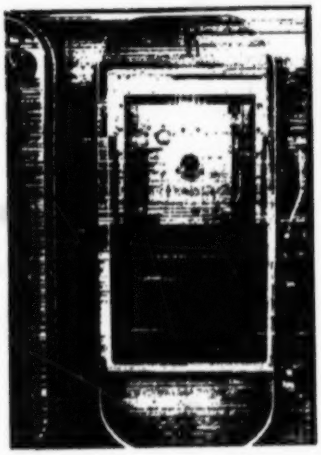
The concept of detection revolves around continuous sampling of the particulates in the air to establish a background spectrum of particle size and frequency; the detection sampling is done automatically with the resulting particle spectrum passed on to the MASU computer. The incoming data is checked through a number of detection algorithms to determine whether an anomalous particle spectrum exists relative to the running average of the background spectrum. If an unusual distribution persists for a specified time, then the detector alarm is triggered and two discrete samplers (of different types) are turned on in each unit to collect samples for identification purposes. The sensitivity of the device is a function of the algorithms selected, and of compromises between absolute sensitivity and false alarm rate. Detection methods are discussed in more detail in the companion paper in this Monograph titled "Detection of Biological Warfare Agents" [Ho].

Two samplers consisting of a Large Volume Air Sampler (LVAS) and the Automatic Dichotomous Sampler (ADS) were deployed. The LVAS consists of a system that draws 600 to 1000 L/min and collects the particulates from the air into a collection fluid (sterile water). The ADS consists of a lower volume rate system (17 L/min) that collects the particulates onto filter disks. Both systems can have sample times that are controlled by the MASU computer and are preset based on the identification test requirements; the identification test sample times can range from 1 to 30 minutes for the LVAS and up to several hours for the ADS.

The two sampler types are complementary in the sense that they overlap in the speed with which a sample may be collected and the concentration of the sample. Having both significantly enhances the probability of successful identification.

When a MASU unit alarms, the responsible CF personnel proceed through a hazard assessment that establishes the overall probability of a biological hazard and the credibility level of the alarm. Based on the conclusions drawn from this assessment, appropriate action could be taken that could include immediately donning Individual Protective Equipment.

The samples collected are taken to MAGIDU where they are analyzed (the analysis procedure initially deployed took 6 hours but was shortened to 3 hours within two weeks of deployment; even shorter times are viable and are being



Mobile Agent Identification Unit Decontamination Tunnel–The MAGIDU was configured with an entry tunnel system permitting operation in both clean and contaminated environments. The entry tunnels had a number of facilities permitting decontamination of personnel prior to entry including a self-contained shower system. Both the MASU's and MAGIDU operated in a positive pressure environment with makeup air coming in through BW/CW air filtration systems.

developed at DRE Suffield). The analysis procedure was standardized, and was completed by in-theatre CF technicians following a short training period. The identification procedure was based on an Enzyme-Linked Immunosorbant Assay (ELISA). ELISA is capable of identifying live and dead organisms, and protein toxin agents. Once specific agents are identified with ELISA, further appropriate action may be taken by exposed personnel and in-theatre medical personnel.

Both the MASU equipment and MAGIDU were housed in ruggedized, citadel environment custom shelters that have provision for primary and secondary electrical power, air conditioning, and both chemical and biological decontamination. All plumbing and electrical provisions were through special entry panel areas utilizing bulkhead sealed connectors and gland seal conduit fittings. MAGIDU has an entry tunnel system that permits normal operations in both clean and contaminated environments.

> The identification procedure was based on an Enzyme-Linked Immunosorbant Assay (ELISA). ELISA is capable of identifying live and dead organisms, and protein toxin agents.

During the deployment, ELISA samples were also collected on a regular basis as part of a screening, "layered protection concept" approach. This provided additional protection in the event that BW agents were delivered in concentrations that were below the MASU detector limits.

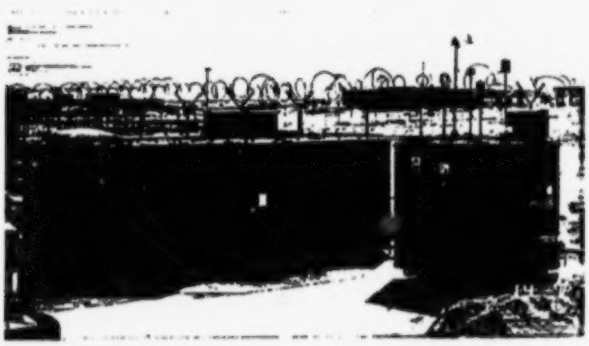
DEPLOYMENT

After the initial design work in October 1990, an intense period of work ensued, culminating in the deployment of four MASU's and one MAGIDU in January and early February 1991. At times, a large portion of the staff of the DSD, the DTD, the Program Support Division and the logistics arm of CFB Suffield, with extensive contractor support, were involved.

MASIF deployment was initiated from Medicine Hat on 23 January 1991 with a team of six DRE Suffield personnel departing for Doha, Qatar by CF C-130 aircraft. This team, consisting of five civilian personnel and one military officer, traveled with four MASU units and associated deployment equipment, and was in-theatre on 26 January. Three of the MASU units were deployed with the Canadian Air Tactical Group Middle East (CATGME) in Qatar, while the fourth unit was deployed with the Canadian Joint Headquarters (JHQ) in Bahrain. All of the MASU units were sited and functional with CATGME by 3 February 1991 and with JHQ by 6 February.

Loading the MASU's onto a CF C-130 Aircraft–Four MASU's and associated ancillary equipment were loaded onto a C-130 aircraft at Medicine Hat airport in preparation for departure on 23 January 1991. All of the equipment was set-up and operational within a few days of arriving in-theatre.

MAGIDU deployment was initiated on 4 February 1991 with a team of 1 DRE Suffield and 3 CF personnel departing for Doha, Qatar. The CF personnel had undergone initial training in the operation of MAGIDU and the conduct of the ELISA procedure at DRE Suffield. This team was in-theatre on 7 February. MAGIDU was sited and functional with CATGME by 10 February. In addition, a capability to conduct the identification procedure was deployed with the US military field hospital in Manamah, Bahrain. This capability was required in parallel with the stand-alone MASU deployed at the Canadian headquarters.



MASU 01 (right) and MAGIDU Deployed with Canadian Air Tactical Group Middle East (Canada Dry 2, Doha, Qatar: 15 February 1991)—Protection for CATGME was provided by MASIF deployed in an array of three MASU units. The master MASU, shown in the photograph, samples the local conditions as well as receiving information by wireless data link from the other two units.

TRAINING

A significant component of the deployment effort was directed towards the training of CF personnel in the operation and routine maintenance of the systems. There was also a strong interest expressed by US Forces in the Middle East in these systems. A number of US Forces personnel were briefed on their capabilities and operational aspects; some US Forces technicians were trained in the collection of identification samples and in the basics of the identification analysis itself.

Some training, particularly in the ELISA procedure utilized in MAGIDU, was conducted at DRE Suffield with CF medical technicians prior to deployment. This allowed the CF personnel to become familiar with the identification test procedure and also provided DRE Suffield staff with the opportunity to refine, optimize and document the procedure for the field environment.

Most of the training, however, was completed while the DRE Suffield deployment team was in-theatre. The in-theatre training was required at both deployment locations as different CF personnel were responsible for the two sites.

This training effort focused on three areas. The first of these was to familiarize the responsible CF personnel with the proper operation of the units, including training for rapid re-deployment to other locations and on the interpretation of MASIF data.

The second area was to provide the background information and hands-on experience to the CF personnel in the day-to-day maintenance of MASIF. This involved the development and documentation of field procedures, several field briefings, and hands-on training in trouble shooting problems.

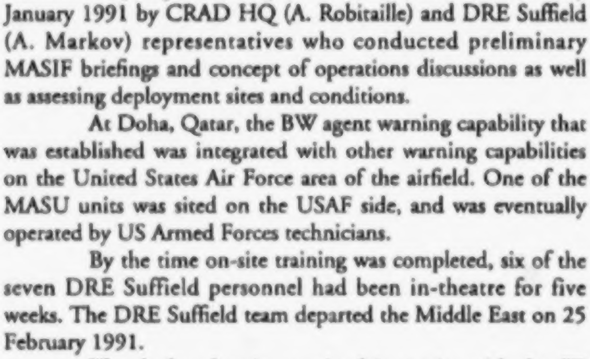
The third and perhaps most difficult area, was the requirement to work with CF operational personnel in the development of a concept of operations for MASIF (as a new system, such a concept of operations had not been previously developed). This had to merge the DRE Suffield personnel's understanding of the effects of the threat, of the sensitivity of the system and of its operational characteristics with CF operational requirements and threat assessments provided by intelligence.

Working with the DRE Suffield deployment team, CF National Defence Headquarters and CANFORME personnel were able to develop a concept of operations that efficiently merged the capabilities of MASIF with the operational requirements and restrictions of the deployment sites. This process was facilitated by a preliminary visit to CANFORME in early January 1991 by CRAD HQ (A. Robitaille) and DRE Suffield (A. Markov) representatives who conducted preliminary MASIF briefings and concept of operations discussions as well as assessing deployment sites and conditions.

At Doha, Qatar, the BW agent warning capability that was established was integrated with other warning capabilities on the United States Air Force area of the airfield. One of the MASU units was sited on the USAF side, and was eventually operated by US Armed Forces technicians.

By the time on-site training was completed, six of the seven DRE Suffield personnel had been in-theatre for five weeks. The DRE Suffield team departed the Middle East on 25 February 1991.

The deployed units remained in service with the CF until the end of the Gulf War and the withdrawal of the CF in March 1991. Although the rapid conclusion of hostilities resulted in a relatively short period of deployment, the equipment remained functional throughout this period and proved capable of successfully operating in the field environment. Initial concerns regarding the sensitivity of the MASU detector units, the possibility of false alarms, and the sensitivity and speed with which the ELISA identification test could be completed, proved unfounded.



Moving MASU 01 into Position (Canada Dry 2, Doha, Qatar; circa 28 January 1991)—Immediately upon arrival in Doha, Qatar, the deployment team set out to inspect and deploy the MASU units. The units were designed for relative ease of movement including movement by forklift, as shown in the photograph, or by helicopter. The latter capability was not utilized during the deployment.

The use of antibiotics being taken preventatively for BW agents by CF in-theatre personnel was stopped part way into the deployment of MASIF.

CANADIAN BW DEFENCE CAPABILITY

The deployment resulted in a significant improvement to the capability of the CF to rapidly detect and identify BW agents. It provided valuable field experience to CF personnel, as well as to DRE Suffield scientific and technical staff, that is directly applicable to planning and implementing improvements to the system and towards developing future generation systems.

Even in this short period of time, MASIF had a noteworthy impact on CF operations, and was a significant factor in reducing and or eliminating the need for a number of preventative measures that were being taken to counteract the BW agent threat. The use of antibiotics being taken preventatively for BW agents by CF in-theatre personnel was stopped part way into the deployment of MASIF. This deployment permitted the implementation of BW agent medical response procedures that depended on rapid response (within the first few hours of exposure) long before exposed personnel would be expected to be symptomatic. Finally, there were significant but more intangible psychological and operational advantages to just having a detection and identification capability against a terrifying and very real threat.

It is also noteworthy that the MASU unit in Bahrain was utilized as a pollution monitor to collect samples and measure the particulate concentrations associated with the oil-well fires in Kuwait. Large changes in the particulate concentrations and distributions were detected within 24 hours of the start of the fires. These concentrations continued to be monitored by Canadian Forces personnel operating the MASU located at the Joint Headquarters after the departure of the DRE Suffield team. Pollution monitoring samples for subsequent analysis were also collected by the CF.

CONCLUSIONS

The rapid development and deployment of MASIF was made possible by a combination of factors uniquely available at DRE Suffield. These included the immediate availability of the scientific detection and identification techniques resulting from the scientific program in bio-chemical defence, DRE Suffield staff's system design, integration and field deployment experience, and the availability of a number of R&D contractors with personnel experienced in the integration and field deployment of military systems. In combination with other measures being taken in-theatre, the units deployed provided the CF with a BW agent detection and identification capability that was of broader scope and sensitivity than any other system deployed by the Allied Forces, allowed other measures (such as prophylactic antibiotics) to be reduced or eliminated, and significantly reduced the risk to CF personnel from the consequences of BW agent attack.

All of the deployed equipment was ultimately returned to DRE Suffield. DRE Suffield completed, with contract R&D support from ADGA Systems International, the engineering documentation of MASIF in sufficient detail to permit the rapid production of additional units. These would be available on short notice to the CF should they be required in the future. Similarly, maintenance and configuration control plans have been developed, also under contract with ADGA, and some improvements to the systems have already been implemented.

As it is not expected that the next generation of biochemical detectors will be available to the CF for several years, the existing units will continue to be available for deployment should the need arise. In the longer term, it is

...concerns regarding the sensitivity of the MASU detector units, the possibility of false alarms, and the sensitivity and speed with which the ELISA identification test could be completed, proved unfounded.

Briefing Canadian and US Forces Personnel at Doha, Qatar on MASU Operations (circa 1 February 1991)–A significant proportion of the effort of the deployment team, while in theatre, was directed towards training Canadian Forces personnel and assisting the CF in developing a concept of operations for the equipment.

DRE Suffield Deployment Team and CATGME NBC Cell Personnel (Qoha, Qatar)–The DRE Suffield deployment team worked closely with Canadian Forces personnel at the Joint Headquarters and at CATGME. Shown in this photograph; in front of MAGIDU at Canada Dry 2, are: Standing (left to right)–Major A. Carruthers (DRE Suffield), Sgt. L. Crandell, Mr. C. Coffey (DRE Suffield), Cpl. Terry Richardson, Mr. D. Saint (DRE Suffield), Sgt. Steve Lanston, MCpl. R. Courtney. Kneeling (left to right)–Mr. D.; Benson (DRE Suffield), Dr. A. Markov (DRE Suffield), Cpl. Pierre Mascotte, Capt. L. Travis (NBC Officer, CATGME). Missing–Dr. J. Ho (DRE Suffield) and Mr. M. Spence (DRE Suffield).

expected that work currently being carried out under a Memorandum of Understanding signed by Canada, the United Kingdom and the United States for the development of an integrated Bio-Chemical Detector (BCD) will continue, with Canada playing a leading role in the development of critical elements of this system. Much of the experience acquired by DRE Suffield during the development and deployment of MASIF will be applied towards the development of the next generation of detector, with the attendant benefits that such field experience brings. Canadian industrial participation is also being sought and is expected to play an increasing role in both the evolution of the existing capabilities and in the development of the BCD.

ACKNOWLEDGEMENT

The development and deployment of MASIF were made possible only through the concentrated team effort of all DRE Suffield staff working with Canadian Forces Base Suffield, CRAD HQ, NDHQ CF engineering and maintenance personnel, Canadian Forces in-theatre support and operational personnel, and industry R&D contractors and suppliers. The support provided by numerous R&D contractors and suppliers, who were, without exception, totally committed to expeditiously providing services, equipment and supplies, was instrumental in successfully developing the prototype systems and in meeting most schedule objectives. Finally, the MASIF deployment team is particularly appreciative of the support provided by the in-theatre Canadian Forces men and women, whose professionalism and hard work facilitated the difficult deployment process. Their tireless logistics and technical support, constructive criticisms, and willingness to accept and work with the DRE Suffield team were essential to the successful deployment of MASIF.

Suggested Reading

S. Penzes, Vibration Isolation Mounting for Sensitive Equipment in the MASU and MAGIDU Shelters, Suffield Memorandum No. 1381, November 1992.

A.B. Markov, Canadian BW Agent Detection System Deployed in the Gulf, The ASA Newsletter, Issue No. 26 (91-5), 9 October 1991.

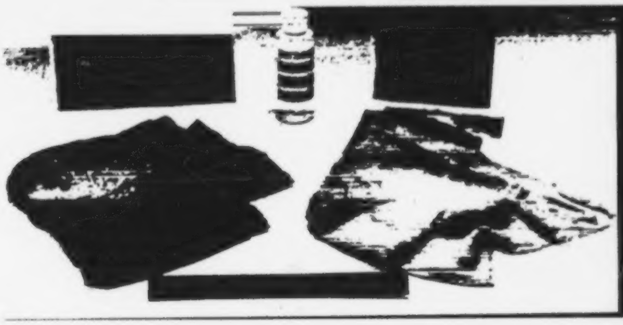
P. D'Agostino, Development of a Chemical Agent Detection System (CADS) for Remote Detection, The ASA Newsletter, Issue No. 26 (91-5), 9 October 1991.

A.B. Markov, Gulf Stories–Last Word on Deployment of MASIF, The Pronghorn Newsletter, No. 7, August 1991.

Anonymous, DRE Suffield Detectors Met Deadline, CRAD Newsletter Special Issue, Volume 2/91, 1991.

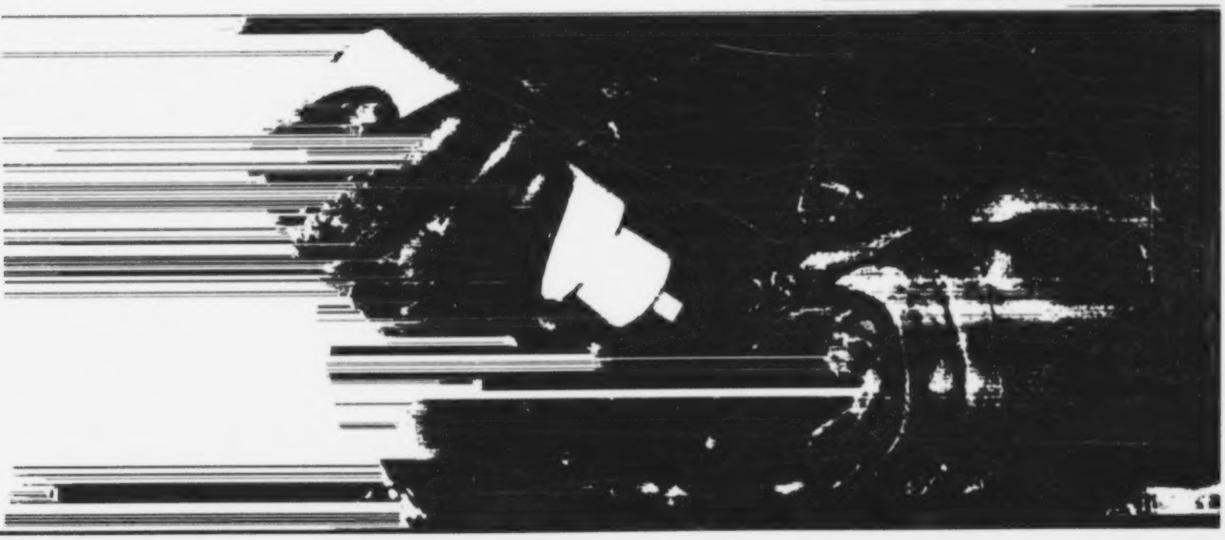
Paul A. D'Agostino and David H. Saint, Remote Detection of Chemical Warfare Agents, Today Science Tomorrow Defence, companion paper.

Jim Ho., Detection of Biological Warfare Agents, Today Science Tomorrow Defence, companion paper.



Above:
Personal Decontaminants (left to right):
Fullers Earth Decontaminating Mitt,
Reactive Skin Decontaminant
Lotion & Towelette

Right:
Canadian Soldier demonstrates the use of
Reactive Skin Decontaminant Lotion



by J. Garfield Purdon

REACTIVE SKIN DECONTAMINANT LOTION

A new skin decontaminant has been developed which significantly improves the Canadian Forces' ability to continue operations in a chemically contaminated environment.

Chemical weapons have been used by a number of countries – most notoriously by Iran and Iraq during their recent conflict – despite a long standing treaty banning their use. The Canadian Forces (CF) can be called upon to operate in a variety of environments, especially in their peacekeeping role, and could face an environment contaminated by chemical warfare (CW) agents. There is a continued need for protective and defensive measures against these agents.

CW agents belong to a number of dissimilar chemical families or groups that present a host of life-threatening and harassing capabilities. Among these families are: vesicants such as mustard gas which cause blistering of skin, eyes and lungs and are percutaneous (penetrate through the skin) and respiratory hazards; blood agents such as hydrogen cyanide which are breathed in and cause death by preventing the normal utilization of oxygen; choking agents such as chlorine gas which injure the respiratory tract and lungs; and nerve agents such as sarin which are percutaneous and respiratory threats and which inhibit the enzyme that prevents the build-up of the neurotransmitter acetylcholine, acetylcholinesterase, leading to loss of motor control and death. The various CW agents of concern in decontamination and their key characteristics are summarised in Table 1.

Protective masks can be used against many of the classical agents since most pose a respiratory threat, but some agents such as vesicants and nerve agents require that skin be protected as well, since they also pose a percutaneous threat. Special clothing, gloves and boots have been developed to protect against the effects of such percutaneous CW agents and new materials and procedures continue to improve this situation. However, even with excellent protective equipment, there remains a requirement to remove and/or neutralize agents

Code	Agent	Effect
HD	distilled mustard gas or 2,2'-dichlorodiethyl sulphide	a persistent vesicant
VX	ethyl S-2 (diisopropylamino) ethyl methylphosphonothiolate	a highly persistent and extremely lethal nerve agent
GB	sarin or isopropyl methylphosphonofluoridate	a semi-persistent lethal nerve agent
GD	soman or pinacolyl methylphosphonofluoridate	a persistent lethal nerve agent

Table 1: A number of CW agents and their effects. Persistence in this context refers to the volatility of an agent; the more persistent the agent, the longer lasting is the hazard and the less volatile it is.

which have come into contact with skin. This may be because of an inadequate warning that agents are present, or due to a sudden surprise in an unprotected state or through breaches in the protective gear in the field. Materials must, therefore, be developed which can be rapidly used to destroy or remove the threat agents before they can be absorbed into the skin. The key elements in the decontamination of skin that has been in contact with CW agents are time and completeness. Nerve agents can penetrate through the skin in sufficient quantities to cause death within five minutes. Also, the lethal dose for nerve agents in particular, is extremely small, e.g., an average dose of 0.01g of VX on the skin per person can cause death to half the personnel exposed. Thus, the challenges in developing an effective skin decontaminant are that it would be fast acting, easy to apply and remove, effective in destroying CW agents and would not irritate skin and eyes.

Nerve agents can penetrate the skin to cause death within 5 minutes and ....an extremely small dose of 0.01g of VX can cause death.

Traditional approaches have used reactive creams, ointments or lotions, e.g., the US M5 and M258A1 Kits and the UK Anti-Gas ointment, or a reactive or adsorptive powder, e.g., Fuller's Earth (FE) and Dutch Powder. Ointments have been the only items which might be used as protective devices (i.e., put in place before contamination of the skin) while powders dominate the decontamination approach. Previous attempts at developing new decontaminants and barriers have encountered difficulties in a number of areas such as irritation to skin or eyes, means of application, retention or removal, interference with other equipment, and agent specificity.

Decontamination of CW agents on skin requires a rapid and effective means of removing or, preferably, destroying toxic substances.

Powders are effective in the laboratory but, in practice, troops often find them difficult to use effectively and to remove afterwards. Among these, FE has been demonstrated to be a non-toxic effective absorber of classical CW agents. Its main attraction hinges on its non-specific high capacity absorbency for liquids and gases, i.e., it is applicable to all liquid CW agents since the removal process is one of physicochemical absorption. It is economical to obtain and can be packaged in bags, dispensing pads and mitts; the FE decontaminating mitt has been a standard CF issue for decontamination of skin and personal protective equipment such as masks, gloves, boots and clothing. Variations of the FE mitt are also standard issue in the UK and AS army inventories although the specific method of application differs from country to country. Despite its effectiveness, FE has disadvantages: it doesn't destroy the threat agents, it creates a dust problem rendering equipment inoperative or obscuring vision in the gas masks, it is deactivated by moisture, and it can cause skin, eye and nose irritation.

A number of countries have tried to develop skin decontaminants but it remains a difficult problem due to the conflicting requirements of rapid action and non aggressive behaviour. One approach undertaken in Germany and the Netherlands involved a search for a protective cream which could be applied before exposure occurred – a prophylactic formulation – so that most of the agent would be prevented from contacting the skin and less-aggressive active ingredients could be employed. Despite some success in the laboratory, such formulations have not been widely deployed. Using a different approach, the US has recently fielded a reactive powder decontaminant which initially absorbs then eventually destroys CW agents.

Barrier Cream/Skin Decontaminant

Canadian research into skin decontaminants began in the seventies with an objective to create a dual-purpose barrier cream and skin decontaminant which could be applied either before a suspected attack as a protective device and/or (re)applied after as a skin decontaminant.

The initial approach was based on complexation of alkali metal ions using compounds known as macrocyclic ethers such as crown ethers and cryptands (see box on p38). Normally, high reactivity of an anion or nucleophile is achieved by selecting a very aggressive or corrosive salt; its high inherent reactivity counterbalances any weakening of its reactivity due to solvation. It was reasoned that complexation of the metal cation of a salt in a non-aqueous solvent by a macrocyclic ether added to the solution might produce a very reactive nucleophile from a

Crowns and Cryptands

Crown ethers and cryptands are organic compounds which, because of their structure, have the ability to complex with or encapsulate certain other atoms, ions or molecules in solution. This property is the result of cavities or "holes" in the crown ether or cryptand structures into which the atom, ion or molecule can fit and be held. In the case of crown ethers, the structure can be visualised as being doughnut-shaped. The atom, ion or molecule which is being complexed fits into the "hole" and is held or attracted by interactions between it and atoms in the crown ether ring surrounding it. The nomenclature used for these compounds indicates the total number of atoms, excluding hydrogen, and the number of oxygen atoms in the ring structure of the crown ether molecule. For instance, one of the most common is known as 18-Crown-6 which has 18 atoms in total and six oxygen atoms, each separated by two carbon atoms (Figure 1). The repeating unit in the crown is the grouping OCH_2CH_2; other crowns of similar structure but with different numbers of repeating units have also been synthesized and characterised as to their abilities to complex other chemical entities.

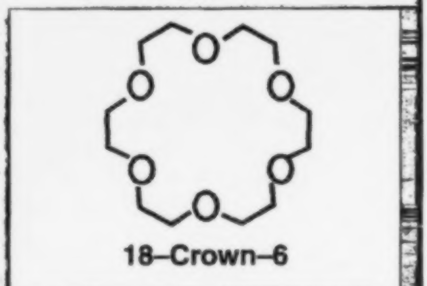


Figure 1: Structure of 18C6 crown ether.

In the case of cryptands, the cavity is three dimensional, i.e. the cryptand molecule resembles a football and the cavity is the interior of the football. Because the atom, ion or molecule being complexed is now surrounded on three sides by the cryptand, it is bound or held even more tightly than is the case for the crowns. The nomenclature in the case of cryptands indicates the number of oxygen atoms involved in each side of the cavity, e.g., cryptand [2.2.2] has two nitrogen atoms, one at each end of the football, the "seams" of the football are chains of two oxygen atoms linked together by two carbon-atom links (Figure 2). Again, the repeating unit is OCH_2CH_2. This grouping is also present in linear polyethylene glycols and their related derivatives and, in fact, the complexation properties of crowns and cryptands are observed, albeit not as strongly, in these non-cyclic relatives (Figure 3).

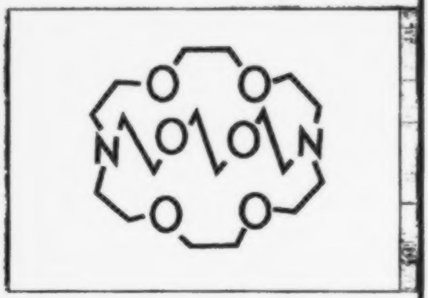


Figure 2: Structure of a cryptand; its 3 D cavity can hold the metal ions more tightly.

Because macrocyclic ethers such as crowns and cryptands complex with metal ions of appropriate size so well, they can aid in the dissolution of salts of these metal ions into non-aqueous solvents into which the salts would not normally dissolve. This is accomplished by facilitating separation of the salt's ion pair, i.e., the metal cation and its counter ion, the anion, in solution (Figure 4)

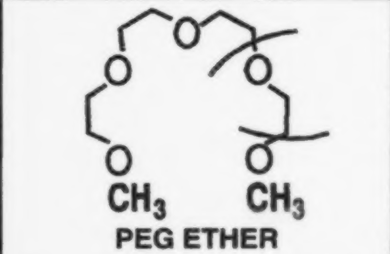


Figure 3: Repeating unit -OCH_2CH_2- is also present in linear polyethylene glycols and their related derivatives and the complexation properties of crowns and cryptands are observed, albeit not as strongly.

In other cases where some salt does dissolve without assistance of an added macrocycle, because there is limited interaction between the ions and the solvent, the ion pair can still remain closely bound together in the solution and thus, the anion will not be available to react easily with anything else. Thus unpairing of the ion pair in solution by addition of a complexer such as a crown can lead to increased reactivity on the part of the anion – a property that would be important in developing the reactive skin decontaminant lotion.

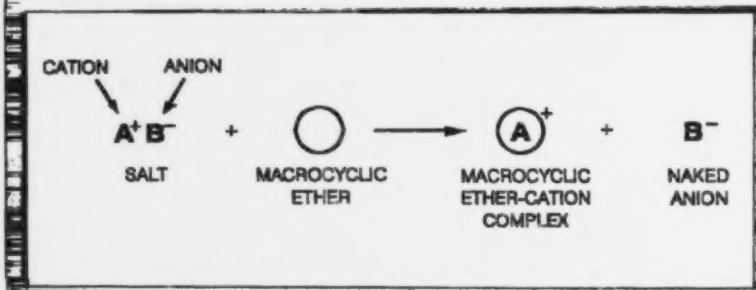


Figure 4: Separation of the salt's ion pair

Nucleophile	Solvent	Decontamination (%)†		Decontamination (Crown) (%)†		Decontamination ([2.2.2]) (%)†	
		HD	VX	HD	VX	HD	VX
Phenoxide	Ethanol	6	26	47	16	49	46
	Tetraglyme	100	100	–	–	100	100
2, 3-Butanedione Monooximate	Ethanol	3	17	36	17	39	30
	Tetraglyme	86	100	–*	83*	100*	100*
Acetone Oximate	Ethanol	12	21	12	36	36	52
	Tetraglyme	insol	insol	100*	100*	100*	100*
Acetophenone Oximate	Ethanol	10	21	17	33	20	43
	Tetraglyme	insol	insol	100*	100*	100*	100*

Table 2: Effectiveness of selected Nucleophile/Complexer/Solvent mixtures against threat agents. Note the reactivity of mixtures including Tetraglyme as the solvent is significantly higher than those using Ethanol and reactivity increases significantly when complexing agents are used (columns 4 & 5).

† Active ingredient in eight-fold excess over agent; complexer in equivalent molar quantities to active ingredient where added. GD, being the easiest to destroy in these systems, was almost always 100%.

* Small amounts (<5%) water added to solvent to assist in solubilization of reagents.

rather benign salt (Figure 4). In this way, nucleophiles powerful enough to destroy CW agents, yet which avoided the highly corrosive effects normally observed with in-service decontaminants, might be found. Many combinations of potential nucleophiles, ion activators and solvents were investigated leading to a four-component system consisting of a nucleophilic potassium salt, a complexation compound, a thickener and a solvent. Among the nucleophiles which displayed significant promise were potassium phenoxide and the potassium salts of several simple oximates including acetophenone oxime, acetone oxime and diacetyl or 2,3-butanedione monooxime. Solvent systems included chemicals such as alcohols, dioxolane, tetraglyme, dimethoxyethane, and polyethylene glycol (PEG)-related compounds.

In-vitro effectiveness of these nucleophiles in two such solvent systems is evident in experiments (Table 2) in which an eight-fold excess of active ingredient and, optionally, an equivalent amount of complexer were reacted at ambient temperature with CW agents for five minutes. In some systems, small amounts of water had to be added to achieve dissolution of the salt.

Two key conclusions may be drawn from this: (a) that the solvent has a profound effect on the reactivity, tetraglyme (dimethyl ether of tetraethylene glycol) supports much higher levels of decontamination than does ethanol and (b) the higher the complexation ability ([2.2.2]>18C6>none), the more reactive the "naked" or unpaired anion.

Linear Polyethers

Although complexers proved to be useful for identification of candidate nucleophiles, their cost, the need for stoichiometric (number of molecules of complexer required for each molecule of active ingredient is a fixed number, usually one) amounts and the need for extensive additional toxicological examination necessitated their replacement by straight-chain analogues. The roles of complexer and solvent were at this point combined in polyethylene glycol (PEG) dimethylethers and the potential field item would be a three-component system. While effective in in-vitro studies and in-vivo trials against CW agents, the mixture based on tetraglyme with Cab-O-Sil™ as a thickener proved to be unsuitable as it dried out and flaked off the skin. Also, despite its advantages of supporting high reactivity, tetraglyme is not a good solvent for these salts. Addition of water or low molecular weight hydroxylic solvents such as ethyl alcohol to increase the solubility of the salts was found to have a detrimental effect on the overall reactivity so seemed contraindicated. Thus, PEG monomethyl ethers (MME PEGs or MPEGs) were chosen as additives to the tetraglyme. Some of these results are given in Table 3.

It is clear that the mixed solvent of 2-glycol MME in tetraglyme results in effectiveness between that found for tetraglyme (high) and ethanol (low) for the oximate salts that are soluble in all three solvent systems. Increase in the proportion of MME in the solvent leads to some decrease in the overall reactivity. On the other hand, using the mixed solvent resulted in improved solubility for the salts over that found for tetraglyme. The decrease in effectiveness in going from tetraglyme to the mixed glycol solvent and with increased percentage of MME in the solvent (see e. g., the 8:1 ratio experiments) is consistent with the earlier behaviour observed for

> ***For reasons of stability, effectiveness and compatibility with skin and eyes, Potassium 2,3- Butanedione Monooximate (KBDO) was chosen as the reactive ingredient in the mixture.***

addition of water or use of ethanol – *the higher the hydroxyl content in the solvent, lower the overall effectiveness.* It was clear that a compromise in solvent composition would be required to improve the solubility of active ingredient on the one hand and the reactivity of the mixture on the other. The eventual solvent/complexer/thickener of choice was a mixture of MPEGs of molecular weight 550-1900 Daltons which possessed the desirable features of the simpler solvents, the thickener, and the complexers but was compatible with eyes, skin and painted surfaces, and was more economical.

From Table 3, it is also evident that the nerve agents (GD, VX) are the easiest to destroy and mustard or HD the most difficult. This is fortunate since the former are the more lethal and rapidly acting agents, so their quick destruction is essential for any proposed skin decontaminant. Also, from these results, the relative effectiveness of the three oximate salts appears to be acetophenone oximate > acetone oximate > 2,3 butanedione monooximate, in direct relation to their degree of dissociation, i.e., the more dissociated or separated the anion is in solution, the more reactive it is. This is in agreement with the very high reactivity caused by addition of macrocyclic ethers described earlier – the more "naked" an anion is, the more reactive it becomes. Based on in-vivo and in-vitro studies, some of which were carried out under an international collaborative effort with defence laboratories in Holland (Prins Maurits Laboratory/TNO), two promising candidates were identified for further consideration as active ingredients in barrier creams: potassium phenoxide and potassium 2,3-butanedione monooximate (KBDO). For reasons of stability, compatibility with skin and eyes, and overall effectiveness, the oximate salt became the eventual candidate of choice as the reactive ingredient in the mixture.

Reactive Skin Decontaminating Lotion

At this stage, the CF placed the emphasis on provision of a reactive skin decontaminant lotion (RSDL) only, which meant that lower molecular weight solvent homologues could be used to provide a less viscous lotion. The active ingredient, which was effective and known to be safe for skin/eyes, and the class of solvents already identified in the barrier cream research above were optimized for less viscous media. In-vivo testing of formulations using the new carriers (PEGs/MPEGs) was performed including studies designed to define the window-of-use (maximum time available after contamination for application to be effective) as a CW agent decontaminant and comparative studies with other formulations and approaches. In all studies, it was evident that the formulations were effective against nerve agents and mustard. Even the base medium provided some protection, i.e., the solvent mixtures themselves possessed the ability to dissolve and retain but not to destroy the CW agents thus drawing the agents away from the skin and slowing their absorption into the skin. This was very fortunate since more time became available for the agents to be destroyed in the decontaminating lotion, i.e., the overall practical effectiveness of a given level of active ingredient was better than might have been expected from in-vitro rates of destruction.

The final formulation was a solution of KBDO (1.25m) and its free oxime, diacetyl monooxime, in a mixture of MPEGs, average molecular weight 550 Daltons, with 10% w/w water added to suppress the freezing point and improve the formulation spreadability. To reduce the pH level, 6% of free oxime was added in the formulation, bringing the pH close to

Nucleophile	Ratio Salt/Agent	2-Glycol MME in Tetraglyme (% V/V)	Decontamination (% in 5 mins)		
			HD	VX	GD
2, 3-Butanedione Monooximate	8:1	14	20	90	100
	25:1	32	45	100	100
	8:1	10	–	99	–
Acetone Oximate	8:1	30	57	96	100
	25:1	45	97	100	100
	8:1	15	–	100	–
Acetophenone Oximate	8:1	14	85	100	100
	25:1	16	100	100	100
	8:1	10	–	100	–

Table 3: Effectiveness of Oximates in Tetraglyme/2-Glycol MME against threat agents

Reactions of RSDL With Agents

For nerve agents, the initial step in the decontamination reaction (Figure 5) is the formation of the phosphonylated oxime. The major final product of KBDO and GB in deuterated chloroform is, however, O-acetyl 2,3-butanedione monooxime, apparently formed by the subsequent reaction of the phosphonylated oxime. Other identified products include acetonitrile and the phosphonate anion. While earlier simulant studies in anhydrous toluene indicated the stoichiometry (number of molecules of one reactant reacting with a molecule of another reactant) between KBDO and nerve agent to be 2:1, more recent simulant studies in MPEG 550/water suggest that the stoichiometry is, in fact, less than 2:1. Although additional reactions between the acetylated oxime and KBDO (Figure 6) may occur under certain conditions, e.g., in acetonitrile, chain disproportionation of KBDO (the first reaction) does not appear to occur in this solvent system.

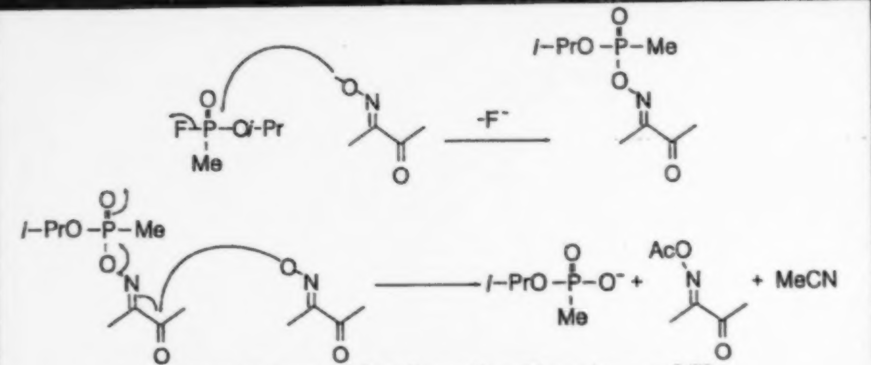


FIGURE 5: Reaction of 2,3-Butanedione Monooximate and GB

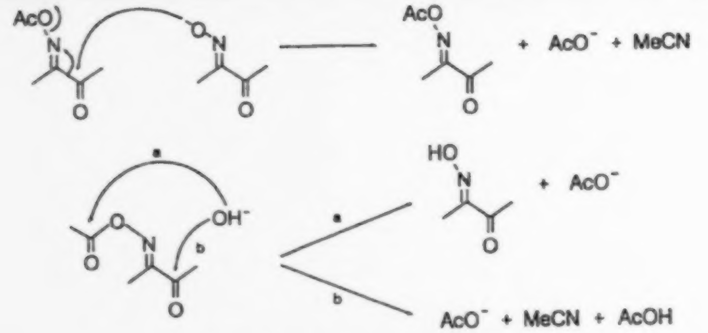


FIGURE 6: Possible fates of Acetylated Oxime

Chain disproportionation or continued consumption of decontaminant by repeated reaction between the active ingredient and one of its products after initially destroying only one molecule of agent would be catastrophic since the decontaminant would be rapidly depleted without further destruction of remaining agent. Thus, it is essential that, in the solvent system selected, the overall stoichiometry of reaction between the active ingredient and an agent be a constant value, preferably low (<2) to conserve decontaminant.

Gas chromatographic/mass spectrometric (GC/MS) spectra have been generated for the products of KBDO with all nerve agents and HD in simple homologues of the RSDL solvent, such as methoxyethanol, in order to characterize and identify the products formed. The GC/MS of a fraction from the product mixture of reaction of KBDO with HD in aqueous ethanol is shown in Figure 7. It is interesting to note the presence of both mono- and di-O-alkyl 2,3-butanedione monooxime substitution products of mustard in 89% yield indicating that the chlorines are replaced by the active ingredient, i.e., the mustard has been destroyed. Also noteworthy is the presence of the tentatively-identified methoxy/oximino derivative indicating that the reaction is susceptible to solvent intervention in methoxyethanol. Efforts are now underway to investigate and further characterize the reaction products in the fully formulated RSDL with the higher molecular weight PEG monomethyl ether as solvent using Thermospray liquid chromatography mass spectrometry (LC/MS) to see if this substitution is maintained and if alkoxy derivatives are likewise generated.

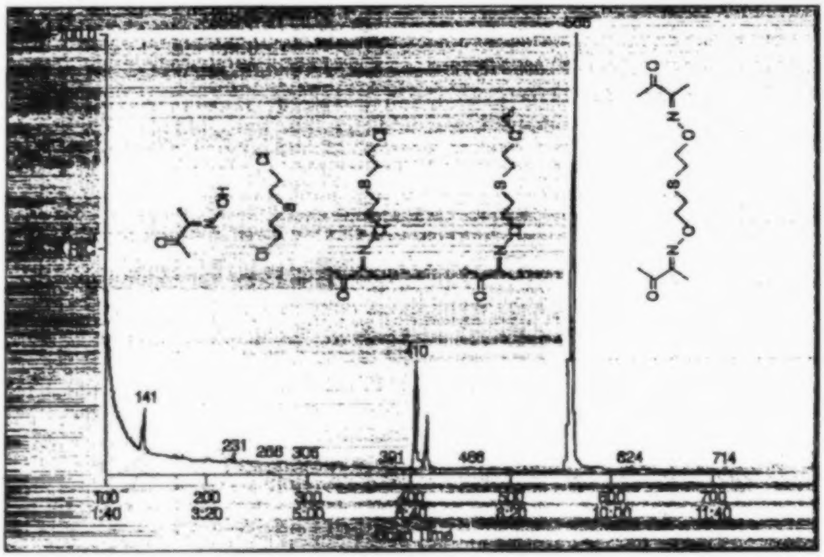


FIGURE 7:
GC/MS of Reaction Products of KBDO and HD In Aqueous Ethanol

10.6. Although water introduced some penalty in reactivity, the formulation was still very reactive and sufficient to meet the requirements.

Reactions of RSDL with CW Agents

Even when in-vivo studies demonstrate that a proposed formulation is effective, a detailed understanding of the reactions involved is essential. First, it is necessary to know if any of the byproducts might be toxic albeit less so than the threat agents. At the outset, it should be noted that in-vivo studies (see below) have demonstrated that the reaction products are not toxic. Second, by understanding the mechanism of the reaction, we can improve its overall effectiveness by optimizing conditions for it. Details of the mechanisms and products of reaction are provided in the box on p41.

Toxicity & Sensitivity

Any skin decontaminant must not be toxic or irritate skin with extended contact such as under a protective mask. Toxicity examinations were carried out using several animal species. First, the low toxicity of KBDO was established in a series of tests covering intraperitoneal, dermal and oral toxicities. Injections of 10 mL/kg body weight of KBDO in aqueous saline were administered to Sprague-Dawley Albino rats and New Zealand White rabbits. For rats, the acute intraperitoneal LD50 (Median Lethal Dose or dosage causing 50% fatalities in an exposed population) toxicity was moderate (405 mg/kg) whereas for the rabbits, the toxicity was relatively low (1175 mg/kg). The same administrations of KBDO yielded significantly lower acute oral toxicities ranging from 950 to 2225 mg/kg. In both intraperitoneal and one oral examination, notable increases in serum potassium levels were considered to be a significant factor in the mortalities. In acute dermal toxicity studies, KBDO, slightly moistened by saline, was administered to at least 10% of the body areas on abraded and intact occluded skin. For both species, the LD50s were greater than 2000 mg/kg and there was no indication that serum potassium levels played a factor. Thus, the active ingredient is deemed safe for use as a skin decontaminant.

Demonstration of low toxicity of the decontamination products is critical to the success of any formulation. The systemic toxicity of nerve agent reaction product mixtures was also investigated in rats. In addition to demonstrating that the RSDL is effective against the nerve agents, the study clearly established that the products have low toxicity even with direct injection.

Several skin a eye irritation examinations were performed on New Zealand White rabbits and guinea pigs, and a chronic skin test was carried out on humans. In contrast to the previous series, the base media was either the same as or very similar to the RSDL. In all cases, including a 21-day chronic irritation and sensitization study trial with humans, the formulation was found to be non-irritating with no sensitization. In the human trial, no changes in serum haematology or biochemical variables were observed.

Equipment Compatibility

Before any new item is entered into the CF inventory, it is necessary to establish that it does not adversely affect or degrade the performance of existing in-service equipment. Thus, compatibility examinations with a number of personal items of equipment were performed.

A detailed examination of the responses of the Chemical

During the Gulf War, 190 Litres of RSDL were deployed in 100-mL flip-top cosmetic bottles.

Agent Monitor (CAM, a device designed to locate surface areas contaminated with CW agent) in the presence of RSDL was performed. The aim was to demonstrate that use of RSDL would not interfere with the function of the CAM, i.e., it would still be capable of detecting CW agents and activating an alarm if the vapours present exceeded preset levels. All ion mobility spectra (IMS) and CAM responses to fresh and aged RSDL, and fresh and aged RSDL solvent, were closely monitored and recorded and the IMS were directly compared to those of HD, GA, GB, GD, GF, and VX recorded on the same CAM. It was shown that properly prepared and packaged RSDL did not interfere with the operation of CAM nor did it cause the CAM to generate any false alarms.

To further reduce the threat to personnel, it is highly desirable that the lotion can be left in place under the mask and gloves. Its compatibility with masks and gloves is, therefore, very important. Exposure of rubber samples from both the olive and black-coloured Canadian C4 respirators and protective gloves to different formulations of the RSDL and barrier cream was studied. Following removal of the formulations, tensile stress, tensile strength, ultimate elongation and tear strengths were found to show no significant change. Other tests found that exposure to the RSDL did not interfere with the operation of a C7 rifle, an area of potentially critical concern.

Conclusions

A new replacement skin decontaminant for the CF is in the final development stages. The advantages of the RSDL include true chemical destruction of CW agents, easy application and removal, compatibility with skin, eyes and protective gear, and low toxicity. Since it is a lotion, the RSDL stays in place after application and, being a liquid, provides for complete coverage easily. It avoids the dusting problems of FE and because it destroys agents, quickly forming non-toxic products, does not have to be removed immediately. The lotion base is completely miscible with water so subsequent showering or washing will readily remove the non-toxic residual lotion. The formulations of the RSDL and related mixtures are now covered by Canadian, US, UK, Dutch and other patents and patent applications and an industrial partner has expressed an interest in producing and marketing it. The RSDL will replace FE as a skin decontaminant in the CF in the 1996-8 time frame but FE will continue to find application as an operational decontaminant for protective clothing and, for the time being, as a personal equipment decontaminant.

During the Gulf War, 190 L of RSDL were prepared (in-house and under contract) and deployed in 100-mL flip-top cosmetic bottles. Sealed pouches, similar to those used for the FE mitt, containing cotton towelettes impregnated with RSDL

Wound Decontamination

A recent observation of the medical use of RSDL on a mustard gas burn strongly suggests that it could be used, without much modification, for this long-standing problem; especially at a time in which large scale demilitarization of old mustard stocks are being undertaken in a number of countries. Despite extensive safety precautions and careful vigilance, a breach in the protective posture of personnel can still occur resulting in painful slow-healing mustard blisters. Such was the case for two workers in Project Swiftsure at DRE Suffield several years ago who suffered mustard burns on their hands. (Project Swiftsure was undertaken to collect and destroy residual amounts of CW agents which had been stored at DRE Suffield since WWII.)

In one patient, normal medical attention was provided; the resulting blister was depressurized under mild detergent solution and the affected area treated with Flamazine. Subsequently, in areas of the skin contacted by the fluid released from the initial blister, additional areas of erythema and blistering appeared and the wound, in general, was painful and raw. Final healing required topical steroid applications and took four weeks.

The second patient reported 24 hours after exposure with a 6x7 cm area of erythemous skin. The treatment regime followed was much the same as before except that debriding of the blister was carried out after the area was covered by RSDL, followed by rinsing in sterile saline and Flamazine treatment. A separate blister on this patient was not treated in this manner but ruptured on its own. In the latter case, as before, new blisters formed wherever the serous fluid contacted the skin. These new blisters were debrided in the presence of RSDL. In all cases in which the debriding was carried out in the presence of RSDL, no subsequent blistering occurred. One week post exposure, complete healing had occurred in those areas in which RSDL was employed whereas the blister which had not initially been debrided in the presence of RSDL required two weeks to heal. While there is no evidence that RSDL improved or hastened the healing process in any way, it apparently prevented further activity; more rapid recovery was the result. Thus, in concert with liberal use of oral and topical antibiotics to reduce infection and other standard medical treatment, RSDL can reduce the pain and suffering and shorten the recovery time for personnel suffering mustard burns.

were also prepared; each towelette provides a single application and is intended to be discarded after use. Fortunately, there was no incident requiring their use.

Further work is continuing in a number of areas including : verification of identification and distribution of agent decontamination products using the final RSDL formulation by LC/MS, characterisation of storage stability and degradation by accelerated aging, development of a foam substrate on which RSDL can be impregnated for packaging, determination of sensitivities of CAM toward CW agents in the presence of RSDL and decontamination products, and estimation of the extent of absorption of KBDO through human skin.

Once these studies are complete and the product specifications and assessment methodology are in place, our efforts to develop a new skin decontaminant will be completed but that will not be the end of the story. Since the active ingredient in RSDL and related compounds are effective against traditional CW agents, it is natural that they be considered for application to other areas of decontamination. Preliminary studies have investigated its possible application to wound decontamination (see box on p43) for which no current satisfactory procedure is available and to decontamination of personal equipment such as protective masks, gloves, boots and gear. It may also be possible to achieve the original objective of creating a dual purpose cream that acts as a protective skin barrier and a decontaminant by suitably modifying the RSDL.

The original objective for developing RSDL was to satisfy a requirement of the CF, the central mandate of the DREs. However, RSDL also has potential civilian applications. For example, some agricultural pesticides such as malathion are related to nerve agents. RSDL has been shown to destroy malathion readily. As well, some vesicants such as nitrogen mustards (2-chloroethyl nitrogen analogues of HD) have been used in chemotherapy. Accidental contact with or spillage of these materials could likely be addressed by RSDL. Efforts are now underway by a DRE Suffield contractor to ascertain if RSDL can be used as a civilian skin decontaminant for a wider range of chemicals.

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VERIFICATION OF THE UNITED NATIONS CHEMICAL WEAPONS CONVENTION

Reducing threat through the development of analytical methods for effective treaty compliance monitoring

by Paul A. D'Agostino, Camille A. Boulet and James R. Hancock

TREATY HISTORY

The use of chemical warfare agents has long been condemned and following the First World War, the 1925 Geneva Protocol, which bans the first use of chemical weapons, was signed. However, this treaty, currently carrying about 120 signatories, did little to curtail the development and weaponization of chemical warfare agents. The resultant world-wide proliferation of chemical weapons led to renewed international pressure for an effective ban on the development, production and use of chemical weapons.

On January 13, 1993, after 25 years of negotiations, a verifiable treaty banning chemical weapons was opened for signature in Paris. The ***Convention on the Prohibition of the Development, Production, Stockpiling, and Use of Chemical Weapons and their Destruction,*** otherwise known as the Chemical Weapons Convention, is an international treaty which will effectively eliminate the world-wide threat of chemical warfare. The success of this treaty depends on its verification provisions. These provisions allow for on-site inspections and chemical sampling and analysis to ensure compliance and identify treaty violations. To date over 150 countries have signed the Chemical Weapons Convention.

HISTORICAL MILESTONES

1907 HAGUE LAND WARFARE CONVENTION FORBIDS USE OF TOXINS OR POISONED WEAPONS.

1915 WORLD WAR I: GERMANS ATTACK CANADIAN POSITIONS AT YPRES WITH CHLORINE GAS.

1917 MUSTARD USED BY GERMANY FOR THE FIRST TIME. DURING WORLD WAR I, 113,000 TONS OF CHEMICALS USED AND RESULTED IN 1.3 MILLION CHEMICAL CASUALTIES.

1925 GENEVA PROTOCOL BANS FIRST USE OF CHEMICAL WARFARE AGENTS, BUT NOT THEIR DEVELOPMENT, PRODUCTION, OR STORAGE.

1936 G. SCHRADER WORKING FOR THE GERMAN CHEMICAL COMPANY, *I.G.FARBEN*, DEVELOPS THE FIRST NERVE AGENT, TABUN.

1945 CHEMICAL WARFARE AGENTS WERE NOT USED BY EITHER SIDE DURING WORLD WAR II.

1969 CHEMICAL WEAPONS CONVENTION NEGOTIATIONS BEGIN IN GENEVA.

1972 BIOLOGICAL AND TOXIN WEAPONS CONVENTION SIGNED. THIS TREATY PROHIBITS THE DEVELOPMENT, PRODUCTION AND STOCKPILING OF BACTERIOLOGICAL WEAPONS.

1983 FIRST OFFENSIVE USE OF MUSTARD BY IRAQ IN THE IRAN-IRAQ WAR. MUSTARD AND NERVE AGENT WEAPONS ARE USED REPEATEDLY UNTIL THE ARMISTICE IN 1988.

1990 COALITION FORCES FACE THE THREAT OF CHEMICAL WARFARE AGENT ATTACK DURING UNITED NATIONS ACTIONS AGAINST IRAQ.

1991 UNITED NATIONS SPECIAL COMMISSION INVESTIGATES IRAQI CHEMICAL WEAPONS CAPABILITIES FOLLOWING THE GULF WAR.

1993 CHEMICAL WEAPONS CONVENTION SIGNED BY 150 NATIONS INCLUDING CANADA.

Following ratification of this treaty, all signatory nations will be expected to minimize or destroy their chemical warfare agent stocks, a process that will take well into the 21th century.

The Chemical Weapons Convention contains specific verification measures to ensure that the provisions and obligations of the treaty are met. Each State Party will be required to make a series of declarations as to past or present chemical weapons capabilities, stockpiles, and production facilities as well as other related activities. These declarations form the basis for a systematic on-site verification process by teams of inspectors from the Organization for the Prohibition of Chemical Weapons, an international body established to monitor treaty compliance. Routine inspections, which relate to specific State Party declarations, will be conducted according to pre-established schedules, protocols, and facility agreements.

Where a State Party has declared a stockpile, the aims of on-site verification are to ensure that no undetected removal or diversion of chemical warfare agents occurs and to confirm the identity, quantity, and destruction of declared chemical warfare agents. For production facilities, the aims of on-site verification are to ensure that production of chemical warfare agents ceases immediately and that the facilities for production are decommissioned according to the provisions of the Chemical Weapons Convention.

VERIFICATION CONFIRMS THE IDENTITY, QUANTITY AND DESTRUCTION OF DECLARED CHEMICAL WARFARE AGENTS

To ensure that prohibited activities such as development and production do not occur, many civilian chemical industries will also be subject to the provisions of the Chemical Weapons Convention and to on-site verification regimes. The Convention establishes three schedules of controlled compounds which are subject to specific verification measures. These schedules are organized according to the threat to the treaty and the impact on the commercial chemical industries.

Schedule 1 contains known chemical warfare agents such as the nerve agents and mustard, as well as their immediate precursors. The scheduling of these compounds will have little industrial impact as they have little or no commercial value.

Schedule 2 chemicals have low to moderate commercial value. The schedule is divided into potential chemical warfare agents and commercial chemicals, such as arsenic trichloride and thiodiglycol, which have legitimate industrial applications unrelated to chemical warfare agent production. A Schedule 2 facility would be subject to specific verification measures based on its production or consumption levels. For these facilities, the general aim of an on-site inspection would be to ensure the absence of any Schedule 1 chemicals and to verify the consistency of declared levels of production, processing and consumption of the declared Schedule 2 chemical.

Schedule 3 contains a number of obsolete chemical warfare agents such as phosgene, hydrogen cyanide and chloropicrin. Schedule 3 also contains high value, commercial volume chemicals which may be used as feedstocks for chemical warfare agent production. Verification measures will also be implemented for Schedule 3 facilities.

In addition to routine inspections, the Organization for the Prohibition of Chemical Weapons may conduct fact-finding missions to resolve non-compliance issues. These fact-finding missions are the strongest measures ever adopted to ensure treaty compliance and may take the form of challenge inspections or investigations of allegations of use. Ultimately, inspectors have the right to take samples for analysis either on-site or in expert, designated laboratories. In cases such as declared storage facilities or production facilities, the identification of chemical warfare agents may be relatively simple because large amounts of sample are available. However, in cases where there is a deliberate attempt to circumvent the treaty obligations, extensive measures may have been taken to obscure any traces of chemical weapons. Because of the serious nature of these inspections, the results of any analyses from samples taken during a challenge inspection or the investigation of an allegation of use must provide unambiguous answers.

GENERAL OBLIGATIONS OF THE CHEMICAL WEAPONS CONVENTION

EACH STATE PARTY UNDERTAKES TO NEVER UNDER ANY CIRCUMSTANCES:

- DEVELOP, PRODUCE, ACQUIRE, STOCKPILE, RETAIN, OR TRANSFER CHEMICAL WEAPONS;
- USE CHEMICAL WEAPONS;
- ENGAGE IN MILITARY PREPARATIONS TO USE CHEMICAL WEAPONS;
- ASSIST, ENCOURAGE, OR INDUCE ANYONE TO ENGAGE IN ANY PROHIBITED ACTIVITY.

AND EACH STATE PARTY UNDERTAKES TO DESTROY:

- ALL CHEMICAL WEAPONS IT OWNS, POSSESSES OR ARE UNDER ITS JURISDICTION;
- ALL CHEMICAL WEAPONS IT ABANDONED ON THE TERRITORY OF ANOTHER STATE PARTY;
- ANY CHEMICAL WEAPONS PRODUCTION FACILITIES IT OWNS, POSSESSES OR HAS UNDER ITS JURISDICTION.

Verification Research at DRE Suffield

The defence community has always realized the importance of establishing the identity of chemical warfare agents and all chemical defence programs contain an identification element to meet this goal. Identification of chemical warfare agents enables the development of appropriate defence postures for detection equipment, therapies, decontaminants, protective clothing and gas masks. Most recently the analytical requirements of a verifiable Chemical Weapons Convention have driven the development and application of new methods for the detection, characterization and confirmation of chemical warfare agents. At present, and in the decade to come, analytical techniques for chemical warfare agents will play an important role in the total verification process as more than 7000 chemicals will be controlled under the terms of this Convention.

DRE Suffield's Mission Statement includes "defence against chemical threats" and "monitoring compliance of weapons control treaties". Both these objectives require DRE Suffield to have a strong analytical capability for the detection and identification of chemical warfare agents. In order to make informed compliance monitoring decisions and to protect its national interests Canada will require the ability to detect and identify chemical warfare agents.

ANALYTICAL METHODS WILL PLAY AN IMPORTANT ROLE IN THE VERIFICATION OF MORE THAN 7000 SCHEDULED COMPOUNDS

Samples suspected to contain chemical warfare agents, their degradation products or related compounds, whether taken in support of peacekeeping and peacemaking military operations or in support of the Chemical Weapons Convention can be treated in an identical analytical manner. Environmental matrices such as soil, water and air, man-made materials such as paint or concrete, and munitions or munition fragments are typical samples which could be, and have been, taken. Common to the analysis of all samples for chemical warfare agents is the requirement for the detection and unambiguous identification of the presence of these compounds in the presence of numerous naturally occurring chemical interferences or background.

In many cases the samples taken may have been exposed to rain, heat, sunlight or wind, for days or weeks and much of the original chemical warfare agent may have evaporated or undergone degradation. This "weathering" process makes verification that much more difficult. The levels of chemical warfare agent contamination could be extremely low in these cases and require sophisticated methods and procedures for their identification. The presence of other significant chemicals, including degradation products may also provide significant evidence and, like a fingerprint, indicate the prior presence of chemical warfare agents.

The DRE Suffield Verification Project was developed with these considerations in mind. Methods for detecting and identifying chemical warfare agents, their degradation products and related compounds were developed and continually improved based on the most sophisticated analytical techniques available. The first part of the project dealt with the development of sample handling and sample clean-up procedures that would be effective for the very low levels of chemical warfare agents which may be found in possible samples. DRE Suffield investigated both solvent extraction and solid adsorbent technologies for the removal of interfering background contaminants.

The Minitube Air Sampling System, a unique system for solid adsorbent sampling, desorption and analysis of airborne samples was developed. This system has been used extensively at DRE Suffield and was deployed in 1992 by DRE Suffield staff to collect air samples for later analysis during the destruction of Iraqi chemically filled rockets under the supervision of the United Nations Special Commission. The system is commercially available from the Canadian Centre for Advanced Instrumentation (Saskatoon) and has been purchased by laboratories in the United Kingdom, Sweden and several other countries for sampling and analysis of air for environmental monitoring.

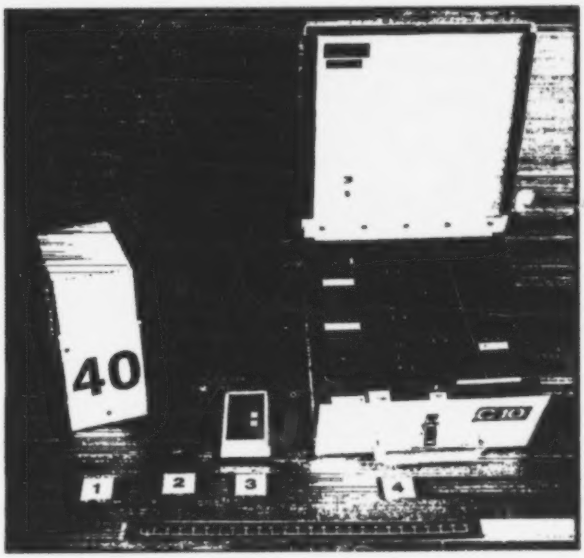


Figure 2: Minitube Air Sampling System: (1) Air sampler, (2) Carousel with sampling tubes, (3) Trigger, and (4) Programmable controller.

The second part of the Verification Project dealt with the development and application of highly sensitive and specific analytical methods for the verification of scheduled chemicals in the collected samples or sample extracts. Minimum criteria have been established for the unambiguous identification of chemical warfare agents and other scheduled compounds for verification purposes. Unambiguous identification requires agreement of acquired spectrometric data with authentic standard reference data using at least two of the following spectrometric techniques; mass spectrometry (MS), fourier transform infrared (FTIR) or nuclear magnetic resonance (NMR). Capillary column gas chromatography was used for the separation of the individual components in sample extracts. Element specific detectors, such as flame photometric detection (FPD, specific to sulfur or phosphorus), MS and FTIR were all researched for application in the verification of scheduled chemicals.

DRE Suffield made significant contributions in the area of chemical warfare agent identification with the most noteworthy being the first reported application of ammonia chemical ionization mass spectrometry (CI-MS) for the characterization of chemical warfare agents and other scheduled compounds. Ammonia CI is now the standard technique employed by laboratories for the determination of molecular weight of organophosphorus chemical warfare agents and the DRE Suffield spectrometric data has been incorporated into the NATO database on chemical warfare agents. This achievement was followed by the first reported application of capillary column gas chromatography tandem mass spectrometry (GC-MS/MS) for the highly specific identification of chemical warfare agents in the presence of extremely high levels of interfering sample components and the application of large volume sample injections for the acquisition of FTIR spectra in samples containing trace levels of chemical warfare agents.

AMMONIA CI-MS IDENTIFICATION OF NERVE AGENTS, FIRST REPORTED BY DRE SUFFIELD, IS NOW A STANDARD TECHNIQUE

Technical Group on Instrumentation

The need for robust analytical methods for the verification of scheduled chemicals which could meet any scientific or political challenge was recognized during treaty negotiations. The Technical Group on Instrumentation was established by the ad hoc Committee on Chemical Weapons of the Conference on Disarmament to address the analytical challenges posed by the Chemical Weapons Convention. This group organized a series of round robin analytical exercises to examine possible inspection scenarios and to evaluate the capabilities of national laboratories and analytical methods. Four round robin analytical exercises were held in 1989, 1990, 1991 and 1993. In each exercise a coordinating laboratory prepared identical sets of samples which were sent to each designated laboratory. The designated laboratories had no knowledge as to the chemicals present or level of contamination of the test samples. Each laboratory was asked to analyze the samples for compounds that would be scheduled under the Chemical Weapons Convention and provide a detailed report for evaluation. Participants included Canada, Australia, China, Soviet Union (two laboratories), United States of America (two

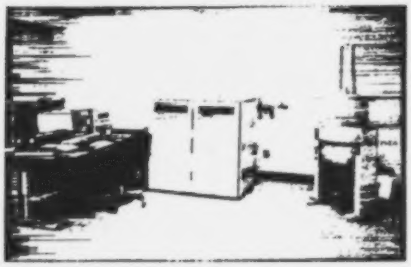


Figure 3: DRE Suffield Nuclear Magnetic Resonance Laboratory.

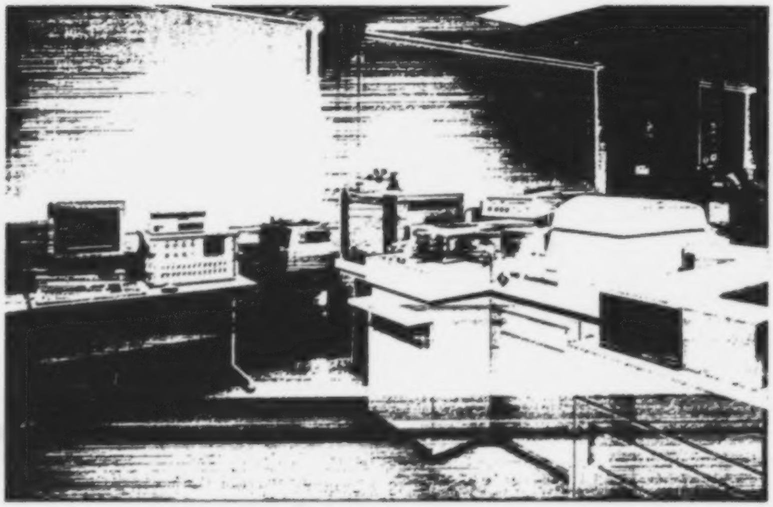


Figure 4: DRE Suffield Mass Spectrometry Laboratory.

laboratories), Finland, France, Germany, India, The Netherlands, Norway, Sweden, Switzerland, Czech and Slovak Republic, and the United Kingdom.

> *FOUR INSPECTION SCENARIOS WERE DEVELOPED TO SIMULATE WAYS A STATE PARTY MAY DELIBERATELY CIRCUMVENT THE TREATY*

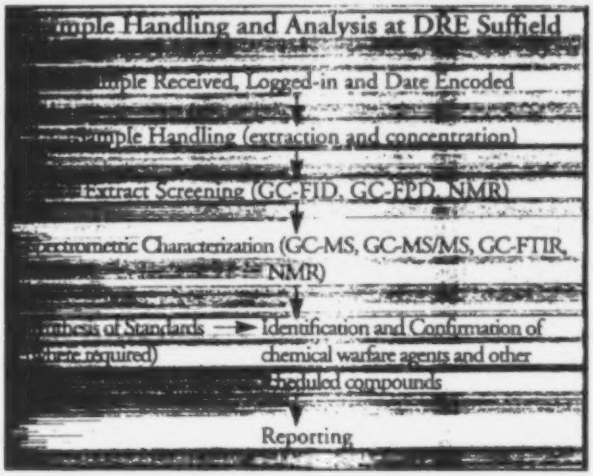
Four inspection scenarios were developed to simulate ways that a State Party may deliberately try to circumvent the treaty including elaborate clean-up to remove any traces of illegal activities. The samples chosen are those most likely to be available during challenge inspections or investigations of allegations of use. These four exercises were:

- Alleged chemical warfare agent use (1989).
- On-site inspection of a chemical industry producing clandestine chemical warfare agents (1990).
- Inspection of a military chemical stockpile (1991).
- Challenge inspection of a suspected chemical production facility (1993).

Alleged Chemical Warfare Agent Use (1989)

A chemical weapons attack would be expected to produce immediate high air concentrations of chemical warfare agents and considerable contamination of surrounding soil and vegetation (environmental samples)[1]. Thus, soil samples were selected as representative of those which may be taken from a battlefield where chemical weapons were reported to have been used. Portions of the four soil samples were sequentially extracted and analyzed using DRE Suffield methods developed for the trace detection and identification of chemical warfare agents and other scheduled compounds.

Mass spectrometry (MS), particularly when interfaced to a chromatographic technique, such as gas chromatography (GC), is the most powerful analytical technique available for the trace detection of compounds in environmental samples. Individual sample components in a mixture are separated by the chromatographic process and then each of the separated components is characterized following ionization and fragmentation in the mass spectrometer. The result, under the most commonly used mode of ionization, electron impact ionization, is a mass spectrum containing mass to charge ions of a pattern specific to the component analyzed. The mass spectrometric patterns for tens of thousands of compounds have been catalogued, including several hundred compounds that would be scheduled under the proposed Chemical Weapons Convention. Acquired mass spectrometric data from the samples circulated by the Technical Group on Instrumentation


mple Handling and Analysis at DRE Suffield
mple Received, Logged-in and Date Encoded
mple Handling (extraction and concentration)
Extract Screening (GC-FID, GC-FPD, NMR)
ctrometric Characterization (GC-MS, GC-MS/MS, GC-FTIR, NMR)
thesis of Standards
here required)
Identification and Confirmation of chemical warfare agents and other scheduled compounds
Reporting

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[1] In fact, this scenario has been validated. Soil samples gathered from a bomb crater reported to be from Iraqi chemical weapons attacks on Kurdish villages were found to contain the nerve agent sarin and mustard. Chemical and Engineering News, May 3,1993.

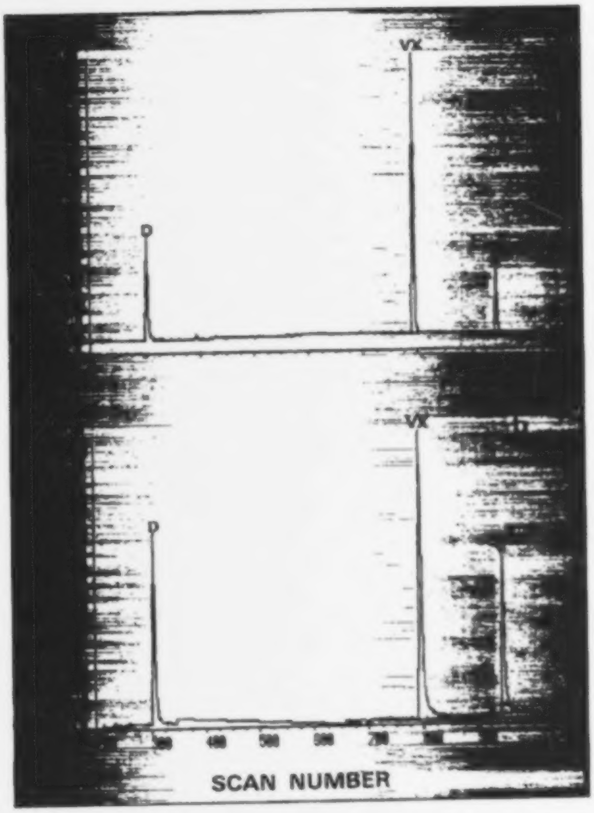


Figure 5: Capillary column GC-MS total ion current chromatograms of the dichloromethane extract of a soil sample under a) electron impact and b) ammonia chemical ionization conditions. Diethyl methylphosphonate (D), VX and bis[2-(diisopropylamino)ethyl] disulfide (S) were detected.

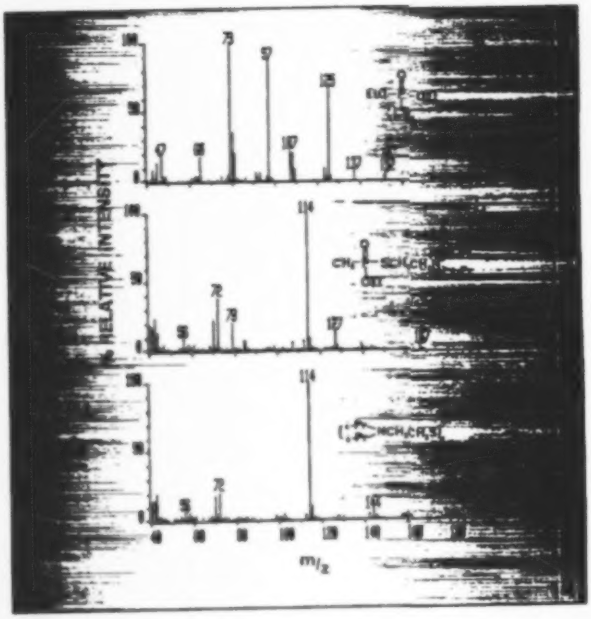


Figure 6: Electron impact mass spectra of a) diethyl methylphosphonate, b) VX and c) bis[2-(diisopropylamino)ethyl] disulfide obtained during capillary column GC-MS analysis.

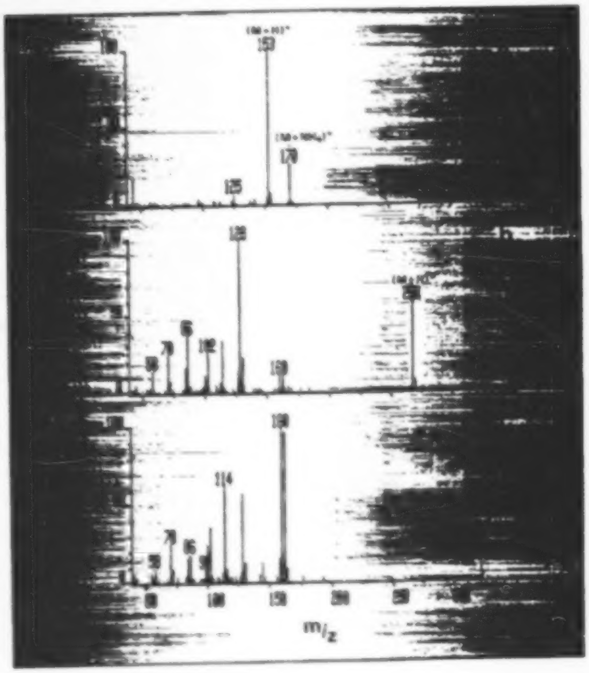


Figure 7: Ammonia chemical ionization mass spectra of a) diethyl methylphosphonate, b) VX and c) bis[2-(diisopropylamino)ethyl] disulfide obtained during capillary column GC-MS analysis.

may be searched against these data base libraries and tentative identifications made based on the degree of match between acquired and library data.

Figure 5 illustrates a typical capillary column GC-MS chromatogram obtained for the dichloromethane extract of one of the soil samples. Mass spectra were obtained under two different ionization modes (EI and ammonia CI) and Figures 6 and 7 illustrate the data obtained for the three major sample components, VX (an organophosphorus chemical warfare agent) and the two VX related compounds, diethyl methylphosphonate and bis[2-(diisopropylamino)ethyl] disulfide. The mass spectrometric data for all three compounds were identical to spectra in the DRE Suffield database, thereby confirming their presence.

Capillary column ammonia chemical ionization GC-MS was essential as the EI mass spectra (Figure 6) of all three compounds exhibited little or no molecular ion information. Only diethyl methylphosphonate exhibited a molecular ion ($M^{+\cdot}$) and the relative intensity of this ion was rather weak. Molecular ion information was acquired and the molecular

Ammonia Chemical Ionization Mass Spectrometry

Reactions taking place in the source of the mass spectrometer that result in the formation of NH_4^+ ions.

$$NH_3 + e^- \longrightarrow NH_3^{+\cdot} + 2e^-$$
$$NH_3^{+\cdot} + NH_3 \longrightarrow NH_4^+ + NH_2$$

Possible ion-molecule reactions between the NH_4^+ ion and a chemical warfare agent, M.

$$M + NH_4^+ \longrightarrow (M+H)^+ + NH_3$$
$$M + NH_4^+ \longrightarrow (M+NH_4)^+$$

weight of each compound was confirmed by the presence of pseudo-molecular $(M+H)^+$ and/or $(M+NH_4)^+$ ions for all three compounds.

Phosphorus and sulfur content was confirmed during capillary column GC-FPD analysis, a technique that specifically detects the presence of these elements in chromatographically separated extract components. Several other compounds related to VX, including non-volatile hydrolysis products of VX, were also identified as their trimethylsilyl derivatives in soil sample extracts.

The presence of VX and several related compounds in the circulated soil samples was clearly established during capillary column GC-MS and GC-FPD analysis and, had these been authentic samples, would warrant an explanation to the Technical Secretariat of the Organization for the Prohibition of Chemical Weapons.

On-site Inspection of a Chemical Industry Producing Clandestine Chemical Warfare Agents (1990)

Chemical facilities, including pesticide plants which use a Schedule 3 feedstock, such as phosphorus trichloride, will be subject to routine on-site verification regimes. Although chemical analysis during these inspections is not automatic, the inspection team may require samples where ambiguities arise during the inspection. Ambiguities include evidence of clandestine operations or large, unaccountable differences in production or consumption volumes of the Schedule 3 chemical. In this scenario, the samples reflected those that could be readily obtained in a chemical plant. Surface swabs of reaction vessels, valves or pipes and liquid samples from storage vessels, waste streams, or plant effluent were prepared to simulate clandestine production of prohibited Schedule 1 compounds.

Figure 8 illustrates a capillary column GC-MS chromatogram obtained during analysis of the dichloromethane extract of a product stream sample. Most of the organic content was accounted for by the presence of the organophosphorus pesticide, Dichlorvos, and several related feedstock or product compounds including diethyl methylphosphonate, trimethyl phosphate and chloroethenyl dimethyl phosphate. The EI mass spectra of all these industrial compounds matched data contained in an environmental data base of EI mass spectra. Full confirmation was possible following GC-MS analysis of authentic reference standards. Dioctyl methylphosphonates, a group of compounds that would be scheduled under the proposed Chemical Weapons Convention, were not contained in any data base and were tentatively identified after fundamental interpretation of EI and ammonia CI-MS data. Unambiguous confirmation was only possible after synthesis of two typical dioctyl methylphosphonates, di-n-octyl methylphosphonate and di-2-octyl methylphosphonate, at DRE Suffield.

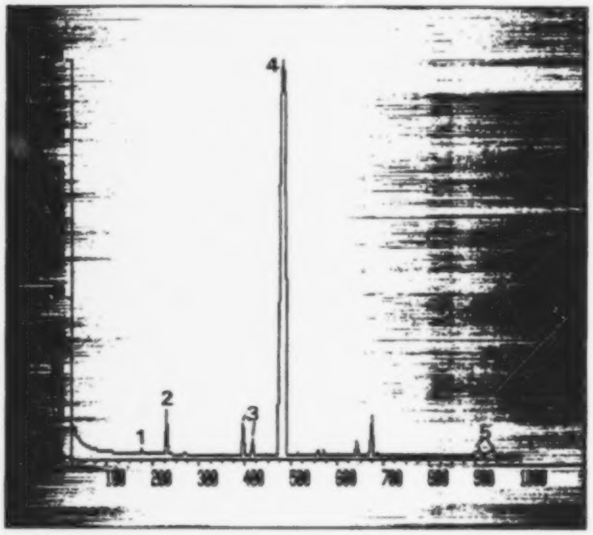


Figure 8:Capillary column GC-MS (EI) chromatogram. Diethyl methylphosphonate (1), trimethyl phosphate (2), chloroethenyl dimethyl phosphates (3), Dichlorvos (4) and dioctyl methylphosphonates (5) were detected.

Many of the samples were also analyzed by a complementary spectrometric technique, NMR, to provide additional data. Extracts, which exhibited phosphorus containing compounds by GC-MS analysis, were directly screened by phosphorus NMR without further sample handling. Because of the large number of components present in these samples, the data was limited to the proton decoupled ^{31}P NMR data which minimizes the problem of overlapping signals which can occur in ^1H and ^{13}C NMR spectra. The identification of dichlorvos as the product of the pesticide production plant was confirmed from the ^1H and ^{13}C data. This data, in addition to the GC-MS and GC-FTIR data, provides complete and unambiguous identification of Dichlorvos.

The samples from this exercise contained numerous compounds related to the production of the organophosphorus pesticide, Dichlorvos, and dioctyl methylphosphonates, a group of rather unique scheduled compounds. Had these been the results of a real pesticide plant inspection, the presence of the dioctyl methylphosphonates would warrant an explanation to the Technical Secretariat of the Organization for the Prohibition of Chemical Weapons.

Inspection of a Military Chemical Stockpile (1991).

To be militarily significant, chemical warfare agents are generally prepared in large quantities, weaponized (put into bombs, artillery shells, or spray tanks) and stockpiled for possible use. Leaking munitions may leave traces of chemical warfare agents in man-made construction materials such as concrete or paint. If munitions were filled from bulk containers at the stockpile, gaskets from valves or door seals may contain residues which could provide evidence of what had been stockpiled at that site, possibly even long after the chemical weapons had been removed. In this round robin, paint panels, rubber gaskets, and concrete samples were prepared to simulate what may be obtained during on-site inspection.

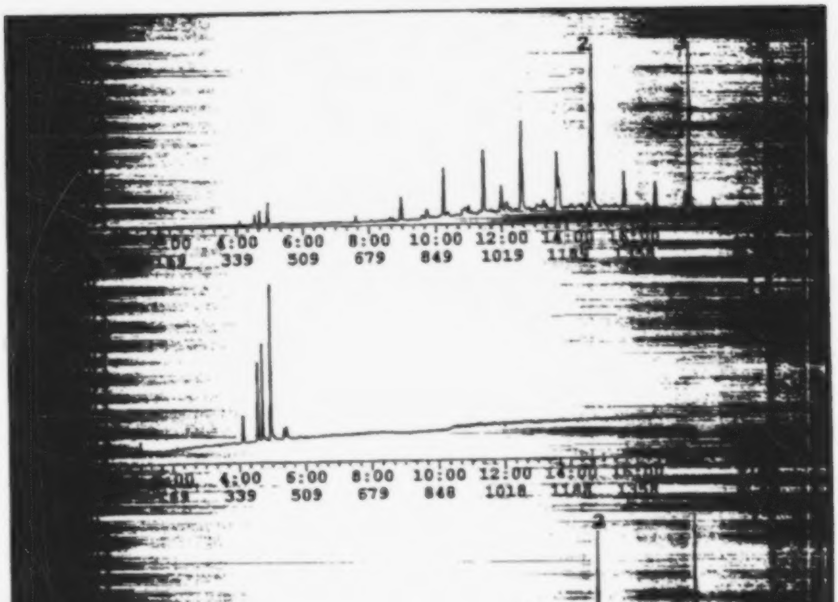


Figure 9: Capillary column GC-MS (EI) total-ion-current chromatograms of the hexane extract of the three painted panels. The second chromatogram was the exercise blank. Sesquimustard (2) and bis[(2-chloroethylthio)ethyl] ether (3) were detected.

Figure 9 illustrates capillary column GC-MS chromatograms obtained during analysis of the hexane extract of the three painted panels. The EI mass spectra (Figure 11) for two of the three scheduled compounds in the extracts (sesquimustard and bis[(2- chloroethylthio)ethyl] ether) were similar to those in data bases. 2-Chloroethyl (2-chloroethoxy)ethyl sulfide was tentatively identified in this extract but the high level of chemical background hindered the unambiguous identification of this scheduled compound by GC-MS. GC-MS/MS was used to obtain the daughter spectra of m/z 123 (an EI ion common to sulfur vesicants) for sesquimustard, 2-chloroethyl (2-chloroethoxy)ethyl sulfide and bis[(2-chloroethylthio)ethyl]ether (Figures 12 and 13). The GC-MS/MS chromatogram obtained (Figure 12) was considerably less complex than that obtained by GC-MS (Figure 9), with the chemical background being reduced dramatically by use of the highly specific GC-MS/MS technique. The presence of sulfur in each of these vesicants was confirmed by GC-FPD.

GC-FTIR couples the separating power of gas chromatography with the structural information available from FTIR. As the gaseous components elute from the gas chromatographic column they pass through a beam of infrared radiation and those components that absorb radiation produce an infrared spectrum. This spectrum is unique to the compound and can either be interpreted for structural infor-

Figure 10: Samples received at DRE Suffield for the 1991 round robin analytical exercise.

mation or compared to data base spectra. GC-FTIR was used to provide complementary spectrometric data for all three compounds identified in the painted panel extracts (Figure 14).

The samples provided contained scheduled sulfur vesicant compounds commonly encountered during analysis of mustard munitions. The presence of these compounds warrants explanation to the Technical Secretariat of the Organization for the Prohibition of Chemical Weapons.

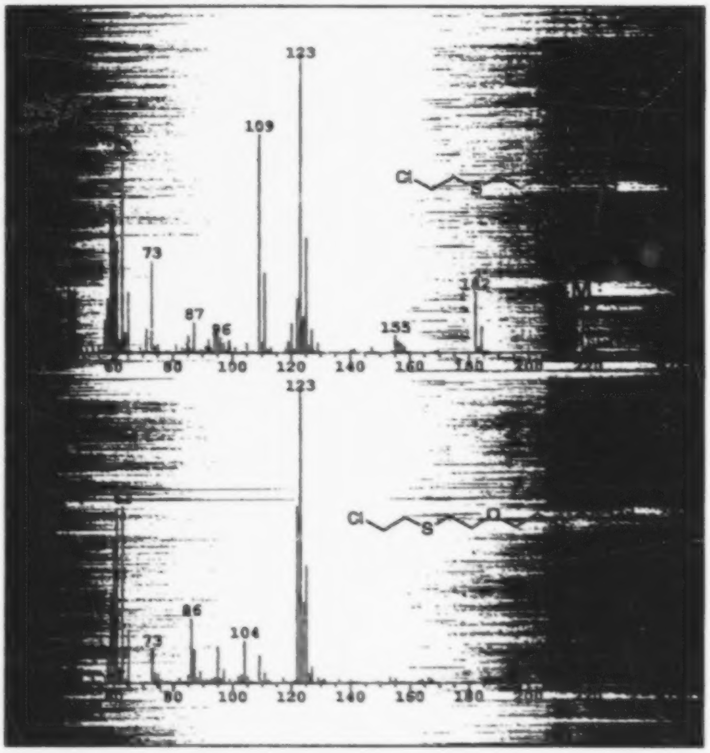


Figure 11: Electron impact mass spectra of a) sesquimustard and b) bis[(2-chloroethylthio)ethyl] ether found in the hexane extracts of two of the painted panels.

Challenge Inspection of a Chemical Production Facility (1993).

In addition to industrial samples which may be taken during a challenge inspection of a chemical industry, other samples may to taken to resolve non-compliance issues. This round robin exercise chose again to analyze water and soil samples and determine to what extent soil types or pH may affect the ability to identify scheduled materials. Soil and water samples may be taken from waste lagoons, effluent streams, or waste pits at industrial facilities and could provide additional information relevant to fact-finding missions. In this exercise, both spiked and unspiked (blank) water and soil samples were distributed for analysis.

As in previous exercises, small amounts of soil were first extracted and compared to reference data. However in this exercise, the extracts of each soil blank were essentially identical to that obtained for the corresponding soil samples and no chemical warfare relevant compounds were initially detected. The soil samples were then further extracted with water or sodium hydroxide-methanol to extract more polar compounds. These polar compounds were derivatized with a trimethylsilyl agent to enhance their volatility and permit gas chromatographic analysis.

Trimethylsilylation of the dried water extracts of the three soil samples resulted in the detection of the trimethylsilyl derivatives of the following Schedule 2 VX or BZ precursors, N,N-diisopropylaminoethanol (as TMS derivative), quinuclidin-3-ol (as TMS derivative) and 2,2-diphenyl-2-hydroxyacetic acid (as di-TMS derivative). No chemical warfare relevant compounds were detected following trimethylsilylation of the dried water extracts of the blanks. All three compounds were confirmed by comparing acquired chromatographic/spectrometric data with that obtained for authentic standards. The dried sodium hydroxide-methanol extracts of the soil samples were taken up in hexane and were essentially identical to their corresponding blanks.

Water samples (without pH modification), and the corresponding blank were not found to contain organophosphorus compounds above the phosphorus NMR detection limit of 10 ppm (detection limits were determined by prior experiments). Analysis of the water samples by fluorine NMR showed

Chemical Sample Handling for Evidence Purposes

As part of the round robins, participating national laboratories were also requested to provide procedures and mechanisms that would be required by the Technical Secretariat for sampling, sample handling, and verification. For the results to have any value in a judicial setting, an elaborate chain of custody is required to ensure that samples are not tampered with, accidentally contaminated, or lost. Based on DRE Suffield experience with sample handling and discussions with personnel from a Royal Canadian Mounted Police Forensic Laboratory, who provided information on the handling of samples for judicial purposes, DRES prepared a manual which details the procedures to be followed within a designated laboratory for sample coding and to maintain a chain of custody during analysis. These detailed procedures have been adopted by the Technical Group on Instrumentation in "Recommended Operating Procedures for Sampling and Analysis in the Verification of Chemical Disarmament", 1993 Edition (ISBN 951-47-8164-3).

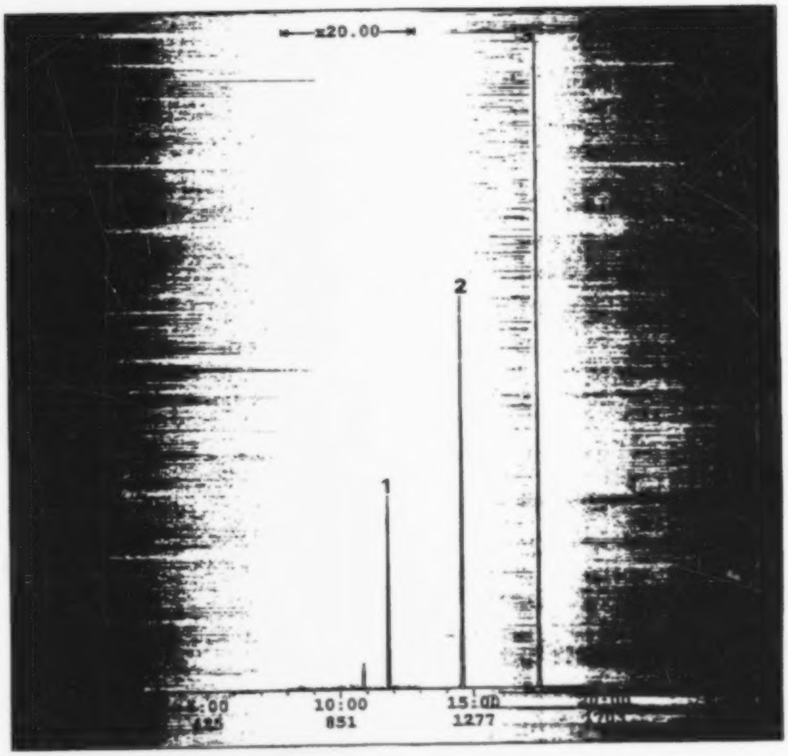


Figure 12: Collisional activated dissociation capillary column GC-MS/MS chromatogram for the daughters of m/z 123 of the hexane extract of a painted panel. 2-chloroethyl (2-chloroethoxy)ethyl sulfide (1), sesquimustard (2) and bis[(2-chloroethylthio)ethyl] ether (3) were detected with considerably less chemical background than in Figure 9.

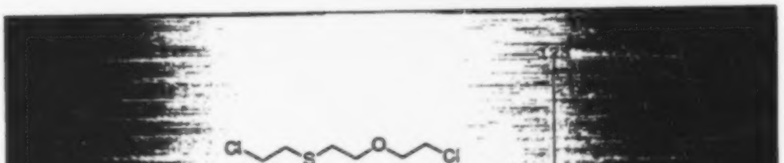


Figure 13: Daughter spectra (m/z 123) of a) 2-chloroethyl (2-chloroethoxy)ethyl sulfide, b) sesquimustard and c) bis[(2-chloroethylthio)ethyl] ether found in the hexane extracts of two of the painted panels.

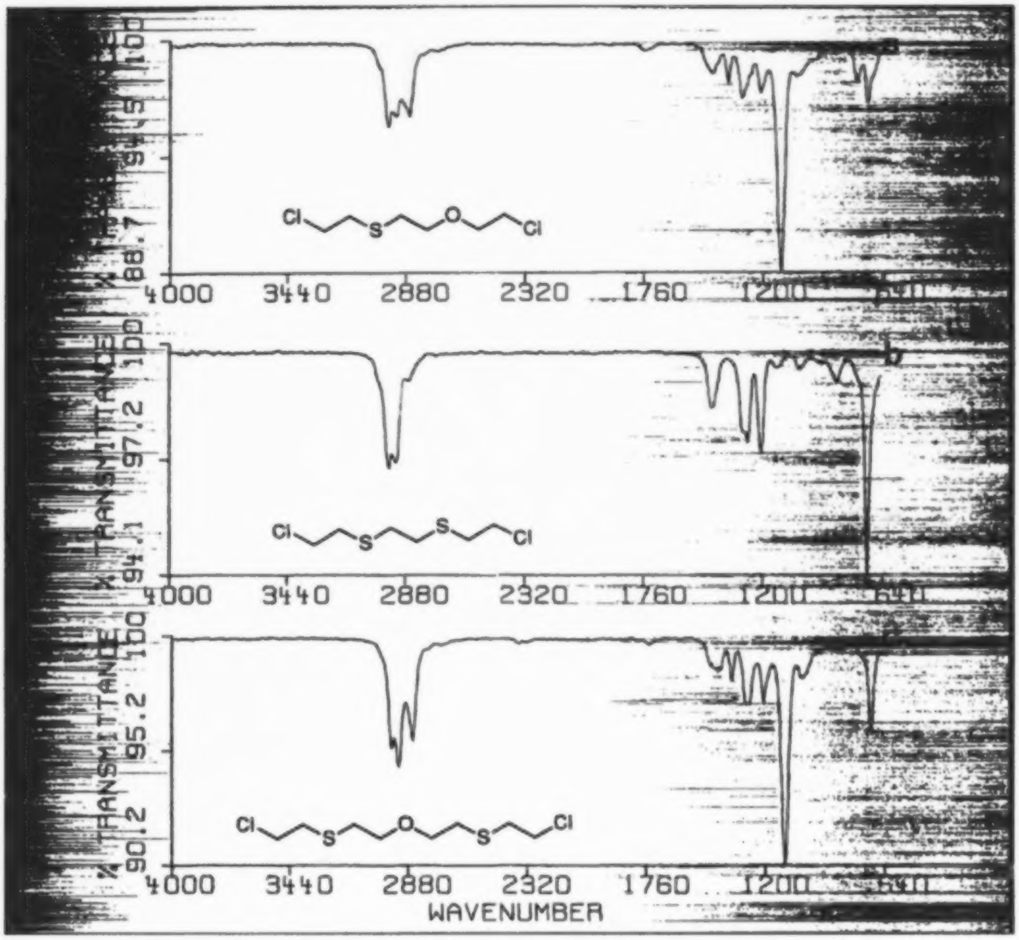


Figure 14: FTIR spectra of a) 2-chloroethyl (2-chloroethoxy)ethyl sulfide, b) sesquimustard and c) bis[(2-chloroethylthio)ethyl] ether found in the hexane extracts of two of the painted panels.

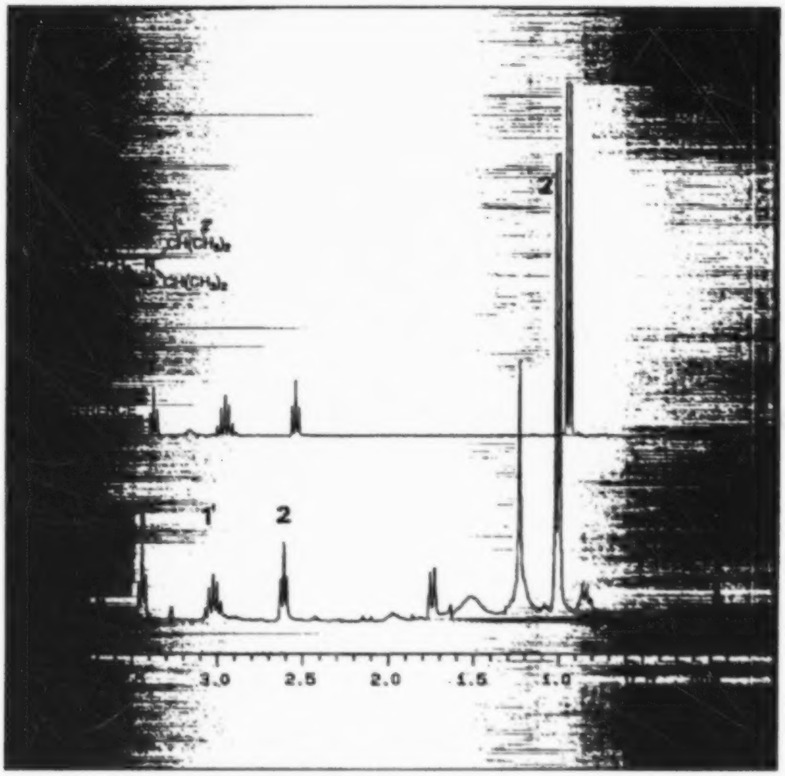
similar results and no relevant organofluorine compounds were detected in either the samples or the blank. Proton NMR analysis of the deuterochloroform extracts did not show any chemical warfare relevant compounds (detection limit of 10 ppm).

The water samples were then processed in a slightly modified procedure to separate and extract organic acids and bases. Approximately 10 mL aliquots of the water samples were first made basic with ammonium hydroxide and extracted with deuterochloroform. These extracts of both water samples clearly showed the presence of N,N-diisopropylaminoethanol. A good quality spectrum, with adequate resolution and signal-to-noise, was acquired which enabled the confirmation of this compound following comparison to an authentic standard (Figure 15).

The aqueous samples were then acidified to pH 2 and analysed by NMR. The first spectrum showed overlap of the residual chloroform peak and the aromatic region of the extract component, 2,2-diphenyl-2-hydroxyacetic acid. By changing the solvent to deuterated dichloromethane, these interferences were removed. 2,2-diphenyl-2-hydroxyacetic acid was identified on the basis of comparison to an authentic standard (Figure 16).

All chemical warfare relevant compounds were confirmed by comparison of chromatographic/ spectrometric data with authentic standard data. Quinuclidin-3-one was synthesized at DRE Suffield to permit unambiguous identification. Only Schedule 2 precursors of VX and BZ were found in the soil and aqueous samples. Extraction of larger volumes of water samples enabled identification of two major sample components by proton NMR. The utility of NMR was clearly demonstrated during the analysis of water samples, as this was the only approach which generated underivatized data for 2,2-diphenyl-2-hydroxyacetic acid. The presence of these VX and BZ precursors would warrant an explanation to the Technical Secretariat of the Organization for the Prohibition of Chemical Weapons.

Figure 15: Proton NMR spectrum of the deuterochloroform extract of an aqueous sample as compared to a reference sample of N,N-diisopropylaminoethanol.



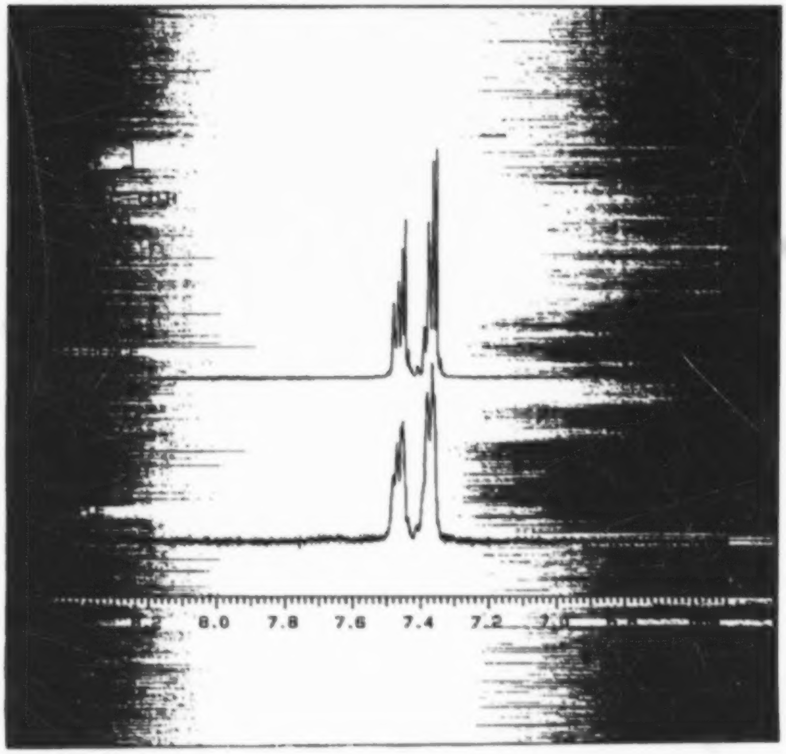


Figure 16: Proton NMR spectrum of the extract of an acidic water sample as compared to a reference sample of 2,2-diphenyl-2-hydroxyacetic acid.

> ***IN EACH EXERCISE DRE SUFFIELD DETECTED SCHEDULED CHEMICALS AND REPORTED THEIR LEVELS***

Conclusion

The United Nations sponsored round robin analytical exercises provided DRE Suffield with an opportunity to demonstrate the applicability of its methods for the unambiguous identification of chemical warfare agents and compounds scheduled by the Chemical Weapons Convention. Ammonia chemical ionization, a technique pioneered for chemical defence applications at DRE Suffield, was demonstrated in all exercises as a critical technique for establishing the molecular weight of chemical defence compounds. The specificity of capillary column GC-MS/MS for the analysis of chemical warfare agents in complicated chemical matrices, such as those that would be encountered on the battlefield, was demonstrated first by DRES. In complex chemical matrices, such as those found during painted panel analysis, MS/MS was especially valuable as this technique allowed DRES to unambiguously confirm trace levels of a sulfur vesicant. GC-FPD and GC-FTIR provided valuable element specific information and class specific spectrometric data respectively. NMR, a complementary spectrometric technique, was most useful in cases, such as the inspection of a chemical industry, where the samples contained a limited number of sample components or highly polar compounds which require derivatization prior to gas chromatographic analysis.

The importance of methods developed at DRE Suffield in these analytical exercises was clearly demonstrated to the Technical Group on Instrumentation. In each analytical exercise, DRE Suffield detected scheduled chemicals, reported their levels and provided the spectrometric data necessary to verify the presence of these scheduled compounds in typical Chemical Weapons Convention samples. The ability of designated laboratories to detect and identify chemical warfare agents under a variety of scenarios has been demonstrated. Chemical analyses provide definitive answers for compliance monitoring of the Chemical Weapons Convention and DRE Suffield analytical methods form a cornerstone of that capability.

Suggested Reading

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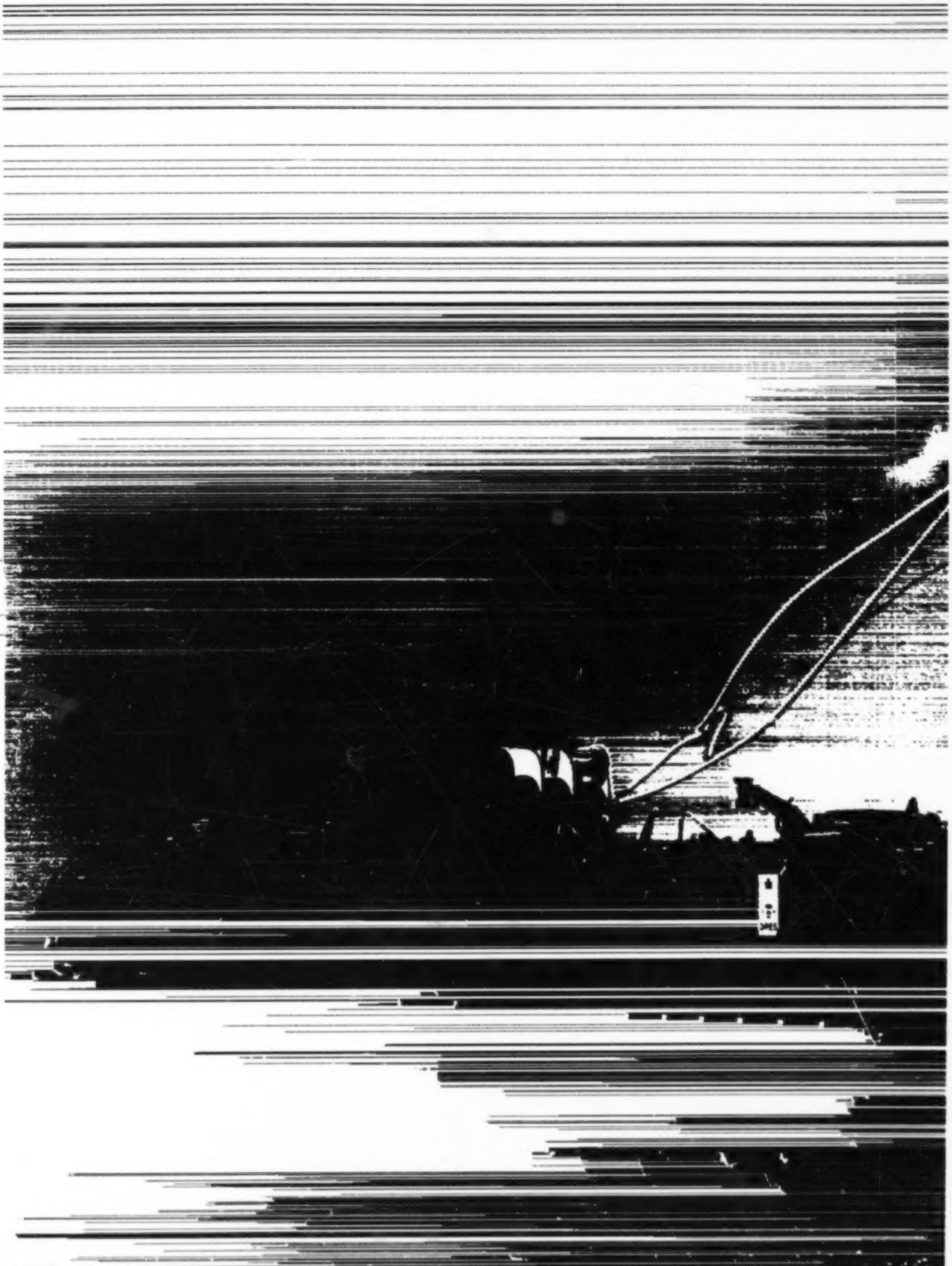
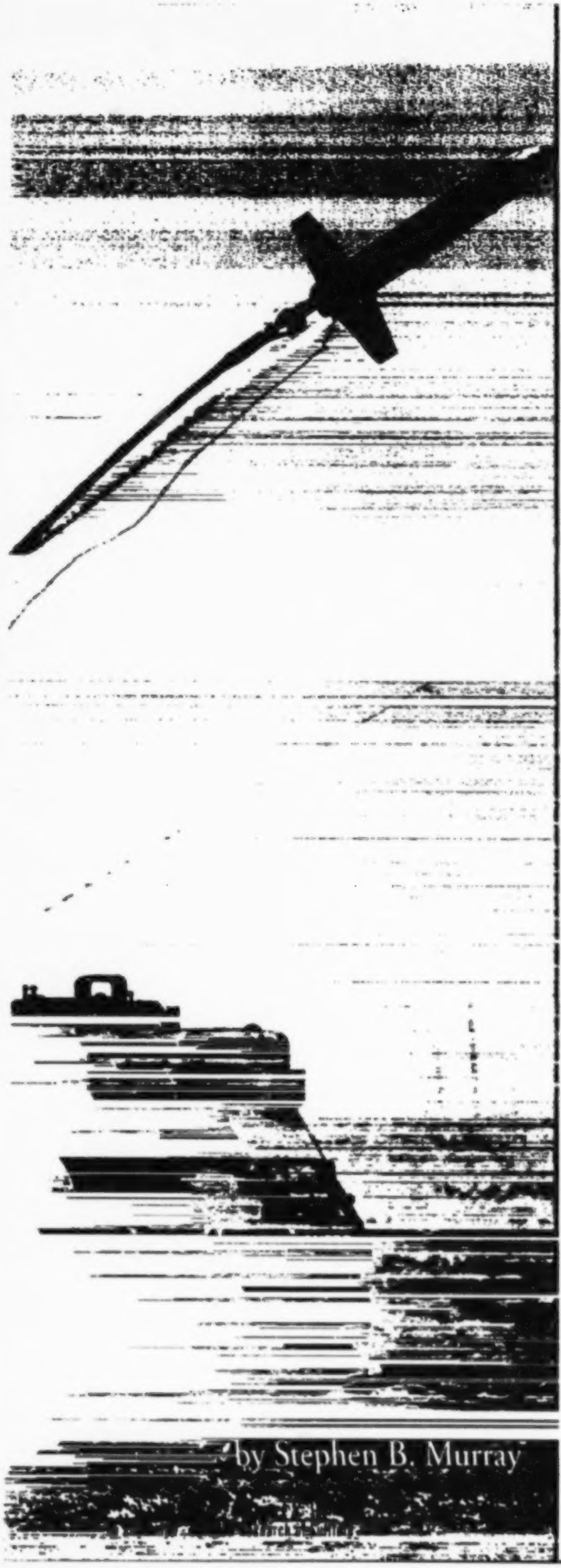


FUEL-AIR EXPLOSIVES

Understanding the basics provides the key to harnessing the power of explosions



by Stephen B. Murray

Background

The Defence Research Establishment Suffield (DRE Suffield) began its investigation of fuel-air explosives (FAE) in 1979. The work was motivated by concerns about the threat that FAE weapons might pose to Canadian Forces personnel in the event of an international conflict. In general terms, it was known from the Vietnam experience that FAE were highly lethal. However, the specific performance of these weapons was known only to the Super Power nations and tended to be a well guarded secret. The high level of classification meant that Canada did not have access to foreign technical reports. This situation, in conjunction with the fact that none of our smaller NATO allies appeared to have an active program in FAE, placed Canada in the difficult position of having to establish a "technology base" from scratch if a proper threat assessment was to become possible.

The laboratory at Suffield was given the go-ahead by the Chief of Research and Development (CRAD) to pursue the technology. This was a logical choice because a fuel-air explosion has many of the same characteristics as the blast wave generated by other types of explosions. Since blast-wave phenomena had been studied extensively at DRE Suffield during the previous 15-year period as part of the Cold War effort to assess the effects of nuclear weapons, a well-developed and relevant knowledge base existed from which to "spring board" Canada part way up the FAE learning curve. In addition, an extensive experimental proving ground was available at Suffield to facilitate large-scale explosive testing.

The FAE program is a classic example of how a CRAD research and development (R&D) program is expected to evolve from infancy to maturity. The early work focussed on developing a fundamental understanding of FAE phenomena. Later, the knowledge base ripened to the point where military applications were pursued with considerable success. Subsequently, some civilian spin-offs emerged.

What is a Fuel-Air Explosion?

As the name implies, the FAE phenomenon involves the explosion of a fuel-air cloud. The fuel can be a gas, an aerosol of liquid droplets, or a dust of solid particles. In a military application the cloud is formed intentionally in such a way that the resulting fuel-air mixture is of stoichiometric proportions. Under these conditions there is just enough oxygen available within the confines of the cloud to support the complete combustion of the available fuel.

high order explosion known as "detonation" can occur if the ignition source is sufficiently strong.

When a fuel-air cloud is ignited, two modes of combustion are possible. In the case of a relatively weak ignition source (e.g., a discharge of static electricity), a low-order explosion known as "deflagration" is observed. A deflagration wave is simply a flame which travels through the combustible mixture at a relatively low velocity (typically tens of meters per second) and generates blast overpressures well below 1 atmosphere. This is the type of explosion that occurs when the family barbeque is lit by a stubborn match. Occasionally, we see media reports of explosions which destroy natural gas heated residences or petrochemical plants. These too are deflagrations. They are relatively tame in comparison with the alternative mode of combustion.

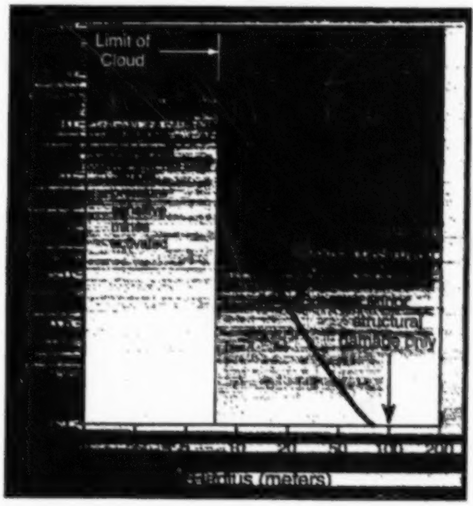


Figure 1: Estimated ground pressure and damage produced by a 40 kg FAE device.

A high-order explosion known as "detonation" can occur if the ignition source is sufficiently strong (e.g., a TNT charge). Detonation of a fuel-air cloud is characterized by a wave which travels through the mixture at velocities in the range between 1,500 and 2,000 meters per second. Corresponding overpressures are typically 15 to 25 atmospheres. From a military standpoint, it is the detonative mode of combustion that is of obvious interest. The damage which can be imparted to various structures is shown as a function of overpressure in Figure 1.

In practice, it is possible to accelerate a slowly moving deflagration wave to velocities of the order of several hundred meters per second by confining the combustible mixture and introducing an array of repeated blunt obstacles in its path. Consider, for example, a long tunnel filled with combustible gas and fitted with a series of regularly spaced pipes oriented transversely to the longitudinal axis of the tunnel. If the mixture is weakly ignited at one end of the tunnel, mild combustion will first occur in the form of a spherical flame propagating outward from the ignition source. As the burned gas expands in the tunnel, it pushes the unburned gas ahead of it. In other words, a flow is induced ahead of the flame. As the flow moves over the first obstacle in the tunnel, turbulence is generated downstream of the obstacle. Eventually, the flame arrives at that location and is entrained into the turbulent flow field. The net effect of this is a sudden increase in the surface area of the flame, a phenomenon known in the combustion field as "flame folding." Because the rate at which the mixture is consumed is proportional to the surface area of the flame, a sudden release of energy takes place. Part of this energy manifests itself as an increased flow velocity. The higher velocity leads to a more intense turbulent flow field downstream of the second obstacle, so that the flame folding process at that location is even more rapid. This phenomenon repeats itself at each obstacle along the length of the tunnel, resulting in a positive feedback mechanism known as "flame acceleration."

Experimentally, it is often observed that a flame speed of about 600 meters per second can lead to an abrupt and violent deflagration to detonation transition (DDT) which usually occurs in the vicinity of one of the obstacles. The remainder of the mixture is subsequently consumed by detonation. Once a detonation wave is established, it is indeed difficult to arrest it. With one or two possible exceptions, detonation has never occurred in an accidental scenario.

Military Advantages of Fuel-Air Explosions

The advantages of FAE over more conventional high explosives (HE) are four fold. The first advantage is that a FAE device contains only fuel. The oxygen required to support the detonation of this fuel is "stolen" from the atmosphere. This is in contrast to HE which already contains the oxygen necessary for combustion. TNT, for example, can attribute 42% of its total mass to oxygen. In practical terms, this means that a higher blast output is possible for a given size of device if fuel-

> *FAE device contains only fuel... a relatively uniform distribution of blast energy is obtained... most fuels are safe... all have the ability to diffuse.*

air technology is employed. Theoretical estimates suggest that a kilogram of some FAE fuels, once mixed with air, can generate the same blast as 10 kilograms of TNT. This is rarely realized in practice (a factor of between 3 and 5 is more typical).

The second attractive feature of FAE technology is that a relatively uniform distribution of blast energy is obtained over the target area. This is made possible by dispersing the fuel into a uniform cloud prior to detonation. A HE charge, on the other hand, releases its energy in a localized region and relies on a shock wave to transport the energy to other locations. The result is a very poor overall distribution of blast energy. From a target vulnerability point of view, this could mean "overkill" in the immediate vicinity of the charge, but total ineffectiveness even short distances away. The poor energy distribution is also characterized by regions of very low blast duration called "skip zones." The probability of defeating certain types of targets in these locations is drastically reduced.

A third advantage of FAE is that most fuels are relatively safe in comparison to HE materials. This is true because they are generally not detonable until dispersed and mixed with air. A final advantage of this technology is that the fuel has the ability to diffuse or be convected to sites which may be inaccessible to other weapons such as guns or fragmentation devices.

The above-listed advantages make FAE more suitable than HE for some military applications including minefield clearing, defoliation of forested areas to facilitate rapid construction of landing strips, demolition of soft targets, and penetration of fortified air-breathing structures. Some of these applications will be described later in the article.

The Status of Detonation Research Prior to DRE Suffield Involvement

In order to appreciate the significance of the contributions made by DRE Suffield and its research partners, it is first necessary to briefly describe the status of research in the detonation field during the late nineteen seventies. In a broad sense, the scientific investigations underway at the time focussed on two aspects of detonation:

(i) the "microscopic" features of the wave, and
(ii) its "macroscopic" behaviour.

Table of Symbols

[illegible]	sonic velocity of the burned gases
[illegible]	critical tube diameter for transmission of detonation
[illegible]	critical energy for direct initiation of detonation
[illegible]	detonation cell length
[illegible]	radius of shock wave or detonation wavefront
[illegible]	critical radius for self-sustained cylindrical detonation
[illegible]	critical radius for self-sustained spherical detonation
[illegible]	time for fluid particles to migrate from the leading shock
[illegible]	velocity deficit
[illegible]	theoretical or Chapman-Jouguet detonation velocity
[illegible]	relative increase in stream tube area or particle surface area
[illegible]	detonation cell width or transverse wave spacing

The term "microscopic" refers to the structure of the detonation wave. Throughout the first two thirds of the century, the wavefront was generally thought to have a one-dimensional structure consisting of a smooth shock wave followed by a zone of chemical heat release. This shock wave and reaction zone complex was believed to propagate at the steady theoretical or "Chapman-Jouguet" velocity, $V_{C\text{-}J}$, named in honour of the two combustion pioneers who first measured these velocities. In simple terms, a shock wave can be thought of as a high-speed surface moving through space and producing elevated pressures and temperatures in its wake. Although this model was modified and refined over the years, the true structure of the wave was not totally appreciated until the early nineteen sixties when American and Soviet scientists reported independently that the wavefront was not the simple entity first envisaged, but instead a highly three-dimensional, nonsteady and cyclic phenomenon characterized by a transverse wave or "cellular" structure. Earlier investigators had observed this structure under specific conditions, but had failed to realize that it was a universal characteristic of detonation.

The cellular structure can best be illustrated by a "smoke record" of the type shown in Figure 2. Such a record is obtained by applying a thin layer of carbon soot, either from a richly burning kerosene lamp or a piece of smoldering wood, to

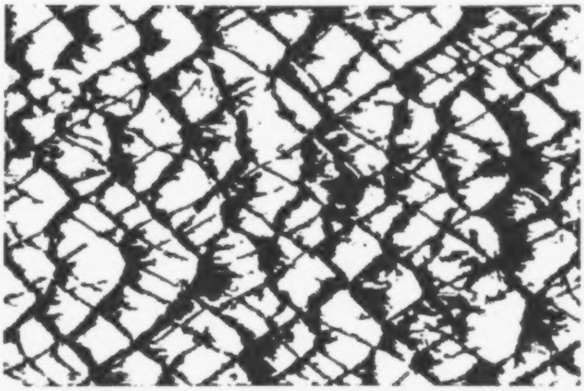


Figure 2: Smoke record produced by a detonation wave propagating parallel to a wall. The gas was a low-pressure mixture of oxygen and acetylene in equal proportions by volume.

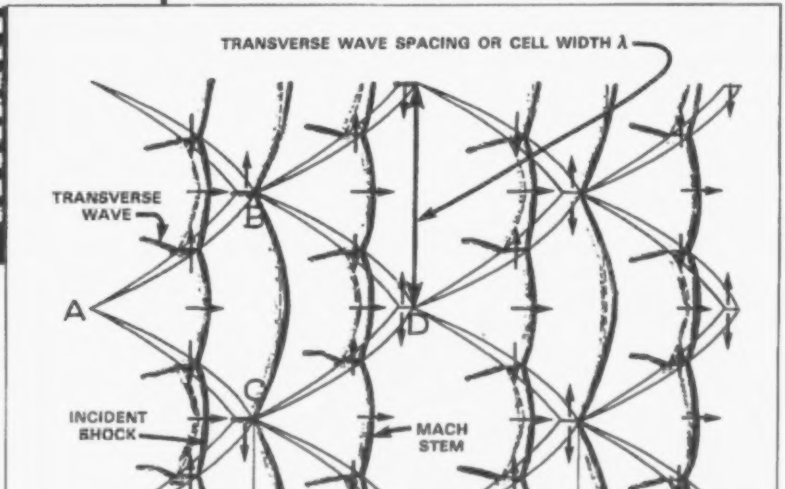
a sheet of mylar, metal or glass. The sheet is then fastened to a wall of the test apparatus and the experiment carried out. The record was "written" by a detonation wave propagating parallel to the sheet. The boundary of each cell is actually a history of the trajectories of shock intersection points associated with the wavefront. The interested reader is referred to the side panel "Cyclic Nature of Detonation" for a detailed description of this complex phenomenon.

Based on this discovery, the cell length, L_C, or cell width λ is the logical choice for a length scale to characterize the gross thickness of the wavefront. The cell size also has practical relevance. It is a direct measure of the ease with which a mixture will detonate. Cells can range in size from a submillimeter scale for mixtures which are highly detonable (e.g., stoichiometric acetylene-oxygen) to several meters for mixtures

Cyclic Nature of Detonation

The diagram below emphasizes the cyclic nature of the detonation phenomenon. Throughout the first half of each cell (i.e., from A to BC), the shock wavelet is highly overdriven. That is, it propagates at about 1.6 times V_{CJ} — the theoretical or Chapman-Jouguet detonation velocity of the combustible mixture. Such a wavelet has been named a "Mach stem" after the German shock physicist Ernst Mach. Since the temperature and pressure behind this wavelet are very high, chemical reaction takes place rapidly so that the zone of heat release trails the wavelet quite closely. We can think of this as a mini "explosion" that results in a pair of shock waves being driven transversely into the neighbouring cells. The boundary of each cell is defined by the intersection of the Mach stem, the transverse waves and the incident shocks of the adjacent cells. These so-called "triple points" are responsible for creating the cellular pattern on a smoke record.

Throughout the second half of the cell (i.e., from BC to D), the wavelet velocity decays to about 70% of the C-J value. The reduced shock pressure and temperature result in the reaction zone falling behind the wavelet so that a sizeable volume of shocked but unburned gas is formed. At this point, the wavelet serves as the incident shock for the more recently generated Mach stems in the neighbouring cells. It is thought that the collision between transverse waves at D, perhaps in combination with the explosion of the preshocked mixture near the end of the cell, gives rise to a rejuvenated overdriven Mach stem to begin yet another cycle. Hence, propagation of detonation is a cyclic, self-sustained mechanism with the heat release from chemical reaction furnishing the driving energy.



Sketch illustrating the cyclic nature of detonation. Blue lines represent shock waves, while yellow regions correspond to zones of heat release. The shock intersection points, shown in black, are responsible for generating the cellular structure characteristic of detonation.

which are very insensitive to detonation (e.g., lean methane-air).

The "macroscopic" aspects of detonation refer more to the global dynamic behaviour of the wave. It was well known, for example, that a minimum quantity of energy, whether from a detonating TNT charge or a spark produced by a capacitor, is required to initiate detonation in a given combustible mixture.

> *hysical boundary conditions play an important role... a detonation wave cannot emerge from a pipe into free space once the pipe diameter is below some threshold.*

Furthermore, the critical energy, E_C, for a given mixture is generally smaller when the gas is contained in a steel tube. In other words, the physical boundary conditions appear to play an important role in determining the detonability.

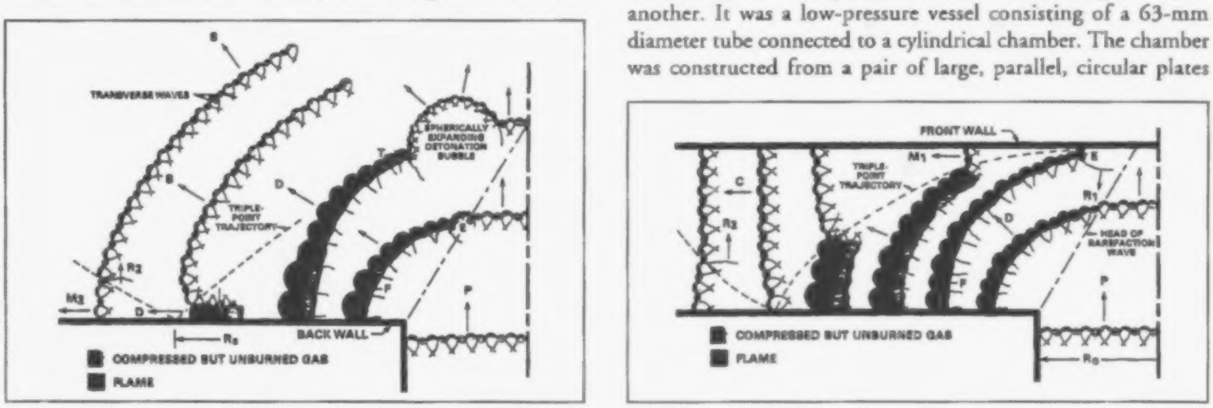
Another macroscopic observation of interest was that a detonation wave in a given combustible mixture cannot emerge from a pipe and continue propagating in free space once the pipe diameter is reduced below some threshold value. This so-called "critical tube diameter," D_C, was of practical interest to the hazard prevention community in that it provided a relative measure of the detonation sensitivity of various gases via tests that were easy to conduct and reproducible from experimenter to experimenter. Gases which were easy to detonate had small critical tube diameters, while those which were relatively insensitive to detonation were characterized by large critical diameters.

A third, interesting observation about the macroscopic behaviour of the wavefront stemmed from detonation experiments in long steel tubes. It had been known for some time that detonation is only possible for a narrow range of mixture compositions in a given size of tube, and that this range widens as the scale of the experimental apparatus increases. Another curious observation was that a detonation wave takes on a deficit in velocity, ΔV, with respect to the theoretical velocity as the detonability limits are approached. Several experimentalists had also noted that failure of the wave appeared to coincide with a relative velocity deficit, $\Delta V/V_{C\text{-}J}$, of about 10%. Explanations for these observations were not clear.

At about the time DRE Suffield began working in the gaseous detonation field, some correlations linking the macroscopic behaviour of the wave to the cell size were beginning to emerge. For example, it was reported that the critical tube diameter was equal to 13 cell widths for a given fuel-oxidizer mixture on a small scale. Papers were also published describing how the cellular detonation front in a tube transforms into a "spinning helical wave" as the cell size approaches the tube diameter. A new school of thought began to emerge from these studies. It was postulated that the critical conditions for sustained detonation depend on how the scale of the cellular structure compares with that of the geometry in which the wave propagates. The elucidation and quantification of this relationship became the focus of the FAE work at Suffield for several years to follow.

Laboratory Studies

An experimental apparatus was assembled by the author to study transmission of gaseous detonation from one geometry to another. It was a low-pressure vessel consisting of a 63-mm diameter tube connected to a cylindrical chamber. The chamber was constructed from a pair of large, parallel, circular plates



Schematic diagrams showing transmission of detonation from a tube to spherical (left) and cylindrical (right) geometries: P - planar detonation wave; C - cylindrical detonation wave; S - spherical detonation wave; D - diffracted shock wave; R - reflected shock wave; M - detonative Mach stem; F - flame; T - transversely propagating detonation wave; E - reignition centre.

Transmission of Detonation from One Geometry to Another

The essential features of transmission from a tube to spherical geometry are shown on the previous page. Briefly, the planar detonation wave emerging from the tube is initially threatened by the sudden expansion originating at the area change. Detonation waves do not like sudden expansions. These tend to cool the gas which has been heated by the leading shock wavelet in preparation for combustion. Cooling causes an increase in the mixture induction time which results in the reaction zone falling behind the shock. As one might expect, the fluid particles nearest the outside of the tube undergo the most severe expansion as they turn through a 90-degree angle and move radially outward along the wall. Locally, this results in the shock wave and reaction zone becoming decoupled. That is, the cyclic cellular mechanism breaks down. New cells are not generated to account for the increase in wavefront area. Existing cells simply grow in size and soon become extinct.

Luckily, not all of the fluid particles in the tube experience the same gasdynamic expansion. The expansion is actually less severe for particles closer to the tube axis. Consequently, there may well exist a core of particles near the axis which is capable of recovering from the expansion. This recovery takes the form of several explosion nuclei which appear spontaneously at the edge of the core. These evolve into expanding detonation bubbles which proceed to overrun that part of the wave heading for extinction. The wave is said to be "reinitiated." Eventually, an established spherical wave propagates radially outward into the unconfined medium.

A similar schematic diagram showing transmission of detonation from a tube to a thin cylindrical chamber is shown in the diagram at the right. The early stages of transmission are identical to those described above. However, reinitiation does not occur spontaneously, but is a direct result of the diffracted wave reflecting from the wall opposite the tube exit. Upon reflection, a cylindrical Mach stem is driven radially outward along the front wall, while a reflected shock wave propagates back toward the tube exit. The pressure and temperature behind the Mach stem are very high, so that reinitiation takes place almost immediately. The subsequent process, whereby the reinitiated detonation engulfs the failing diffracted wave, is very similar to that described previously.

he survival of the wavefront depends on two competing processes: the rate of chemical reaction and the rate of gasdynamic expansion.

separated by an annular spacer. In this apparatus, a detonation wave initiated at the closed end of the tube propagates along its length and subsequently negotiates a sudden area change at the tube exit.

A small separation between the plates permitted the planar detonation in the tube to transform into a cylindrical wave in the chamber. Alternatively, the transformation of planar detonation to spherical detonation (the critical tube diameter problem) could be studied by using a very large plate separation. In other words, the severity of the expansion imposed on the wave emerging from the tube was controlled by the plate separation. The rate of chemical reaction, or equivalently the cell size, was controlled by adjusting the mixture composition and initial pressure.

A photograph showing successful transmission of

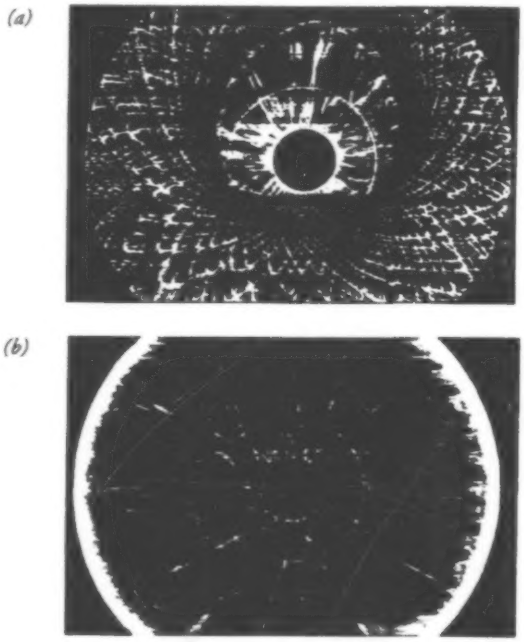


Figure 3: Open shutter or time integrated photographs showing (a) successful transmission of detonation from the tube to the cylindrical chamber, and (b) failure of the wave to negotiate the area change.

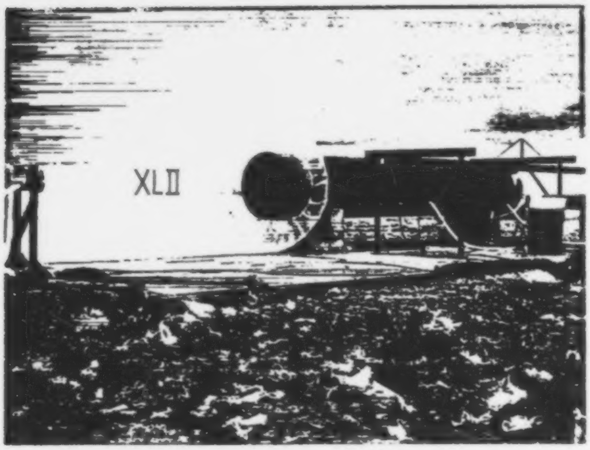


Figure 4: Large-scale apparatus used to study the transmission of fuel-air detonations from planar geometry to spherical geometry. The tube is 1.83 meters in diameter. The large plastic bag is intended to represent free space.

detonation from the tube to a thin cylindrical chamber appears in Figure 3a. The cellular structure was captured on film by a camera positioned on the tube axis looking normal to the direction of propagation in the chamber. Figure 3b shows the result for an unsuccessful attempt to transmit from one geometry to the other. Note the absence of cellular structure. Based on numerous tests employing pressure measurements, photography and smoke records, comprehensive descriptions of the transmission phenomena were proposed. The interested reader is referred to the side panel "Transmission of Detonation from one Geometry to Another" for details.

The survival of the wavefront depends on the outcome between two competing processes; the rate of chemical reaction and the rate of gasdynamic expansion. On the one hand, the shock front heats the gas particles so they eventually burn following a short delay period. On the other hand, the expansion subjects the shock-heated particles to gasdynamic cooling. If the rate of cooling is rapid in comparison with the rate of reaction, the particles might never undergo combustion, or they might do so too late for the combustion energy to be of use in supporting the shock front.

Three significant correlations emerged from this study. Firstly, it was verified that $D_C \cong 13\lambda$ for low-pressure, acetylene-oxygen mixtures. It was also found that the critical radii for self-sustained detonation in cylindrical and spherical geometries are 4 cell lengths and 8 cell lengths, respectively; that is, $R_C^* \cong 4L_C$ and $R_s^* \cong 8L_C$. Detonations cannot exist for smaller radii because the gasdynamic expansion is too severe for survival of the wave.

The tests described above were for a single fuel-oxygen system on a laboratory scale. What was not clear to scientists was whether these conclusions were of a universal nature. Would D_C always be equal to approximately 13λ, say for a fuel-air mixture in a large tube? Would the critical radii for self-sustained cylindrical and spherical detonation be $4L_C$ and $8L_C$, respectively, for all detonable mixtures?

Field Studies

In order to address these questions, field studies were undertaken to determine the critical conditions for transmission from much larger tubes. A photograph of the largest tube (1.83-m diameter), sitting on concrete pedestals, is shown in Figure 4. In these experiments, a cylindrical plastic bag was attached to the exit end of the tube to simulate the "unconfined." The bag diameter (3.7 meters) was chosen so that the bag walls would not interfere with transmission. Prior to a test, the entire tube/bag volume was filled with a fuel-air mixture. Initiation of detonation was achieved using either a high-explosive charge, or a slug of energetic and easily detonable gas, positioned at the end of the tube opposite the bag. For such a large test apparatus, it would be necessary to employ fuel-air mixtures characterized by large detonation cells if cell size scaling was to hold true. Accordingly, the fuels used in the study included acetylene, hydrogen, ethylene, ethane, propane, butane, and hydrogen sulphide. Stoichiometric mixtures of these fuels with air led to cell sizes in the range between 10 and 700 mm.

High-speed cinematographic records show both failure of transmission and critical transmission of detonation from the tube to the bag. As in the laboratory study, reinitiation of the wave occurs near the central axis about one tube diameter from the exit. This is very near the location where the expansion wave originating at the edges of the tube converges on the axis. The latter frames in the sequence show the reinitiated detonation engulfing that part of the diffracted wave heading toward extinction.

Although there was some judgement involved in estimating the cell size from smoke records generated by fuel-air detonations, these field studies demonstrated that the critical condition for transmission could indeed be expressed in terms of D_C having to be a specific multiple of λ. Whereas the constant of proportionality had been 13 for the fuel-oxygen system used in the laboratory, it was found to be somewhat variable for the fuel-air systems, ranging from approximately 11 to 17 for most of the fuels tested. Although it would later be postulated that the regularity of the cellular structure, and not just its scale, plays a role in determining the detonation sensitivity, the variation in the constant of proportionality was considered to be relatively small given the increase in the scale of the apparatus (by a factor of nearly 30) and the difficulty in measuring cell sizes. Thus, the notion of a universal criterion for self-sustained detonation was still considered to be largely valid.

The difficulty with transmission experiments from a theoretical point of view is that they are highly three-dimensional and transient in nature. In simple terms, this means that each particle entering the detonation front experiences a

[illegible] "Stream Tube" Analysis [illegible] to Diverging Wavefronts

[illegible] the diverging wavefront shown in the diagram below. If the wavefront is of radius R, then the surface area of the front is $k(R)^j$ where $j = 1$ or 2 and $k = 2\pi$ or 4π for cylindrical and spherical geometries, respectively. Assuming that detonation Chapman-Jouguet conditions prevail throughout the reaction zone, the particles entering the leading shock wave fall behind it a distance of one cell length L_c in time $\Delta t = L_c/C_{CJ}$, where C_{CJ} is the sonic velocity of the burned gases leaving the reaction zone. But during this interval, these particles reach a radius of $R + (V_{CJ} - C_{CJ})\Delta t$ where [illegible] the velocity of the diverging wavefront. Therefore, the relative increase in the area of the particle surface or, equivalently, the relative increase in the area of the stream tube of particles behind the wavefront, [illegible] is given by:

$$[illegible]$$

[illegible] the above equation to obtain the normalized wavefront radius in terms of the relative [illegible] increase gives:

$$[illegible]$$

[illegible] found that $(V_{CJ} - C_{CJ})/C_{CJ}$ from equilibrium calculations is typically 0.8 for combustible gaseous mixtures, and setting [illegible] to denote critical conditions, the analysis gives critical radii of $R_c = 4L_c$ and $R_c = 8.4L_c$ for cylindrical and spherical geometries, respectively. In other words, particles entering [illegible] cylindrical wavefront having a radius of four cell lengths will experience a relative stream tube area increase very near the critical value [illegible]. The corresponding radius in spherical geometry is 8.4 cell lengths.

These values are in good agreement with the critical radii observed in experiments on the transmission of detonation from a tube to cylindrical and spherical geometries.

he rate of gasdynamic expansion was controlled by the selection of the polyethylene wall thickness.

different history as it proceeds through the reaction zone. A practical consequence of this is that such problems are often difficult, if not impossible, to analyze. Thus, although it was believed that a universal criterion for self-sustenance did exist, there was little hope that the precise nature of the criterion would be identified from transmission studies. It was now that scientists began to search for an experimental configuration that would allow them to control the gasdynamic expansion imposed on the wavefront and, as well, make possible a simple, steady-flow approach to analysis.

A novel, yet simple, experiment was eventually devised to meet this challenge. The configuration, shown in Figure 5, consisted of a thin-walled, extruded, polyethylene tube filled with a detonable gas. Initiation of detonation in the tube was achieved at one end by either a high-explosive charge (as shown in the photograph), or by an established planar detonation wave emerging from a steel pipe of the same diameter. As before, the cell size in these experiments was controlled by varying the composition of the combustible mixture. The rate of gasdynamic expansion imposed on the wavefront was controlled by the selection of the polyethylene wall thickness. This means of controlling the expansion was ideal. In the one limit, a very light wall (e.g., plastic cling wrap) would accelerate rapidly when subjected to the high-pressure conditions behind the leading shock wave. This would cause the reacting gas to experience a

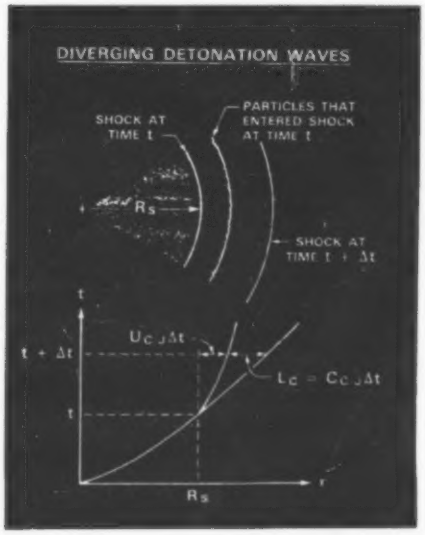


Diagram showing diverging detonation front and corresponding radius-time plot.

very severe expansion. In the other limit of a heavy polyethylene wall (e.g., credit card plastic), the reacting gas would experience a negligible expansion because the wall would not accelerate appreciably until after the passage of the wavefront. Any severity of expansion between these two extremes could be arranged simply by adjusting the wall thickness.

eveloping an inexpensive, reliable and expedient procedure for clearing mine fields.

A photograph showing the detonation wave at a point part way down the tube appears in Figure 5. It should be apparent that the angle of the deflecting wall, as well as that of the shock wave in the air surrounding the tube, are independent of the position of the wavefront. Likewise, the curvature of the front is independent of position. The photograph in the figure would look the same whether it was taken 10 meters from the initiation end of the tube or 100 meters from the end. In other words, to an observer "riding" on the wavefront, the flow is globally steady. Fluid enters the shock wave and is exhausted from the reaction zone at a steady rate. Because the flow of gas between the shock front and reaction zone is subsonic, the wavefront can adjust its curvature so that each gas particle entering the front experiences the same thermodynamic history. A diverging wavefront does not exhibit these features. The continuous tube configuration makes possible a steady, quasi one-dimensional analysis of the problem.

Using this apparatus, numerous tests were conducted in which the critical cell sizes were identified for successful propagation in tubes of various wall thickness. A numerical model was developed to calculate the radial acceleration of the plastic wall in the wake of the leading shock front and, hence, the severity of the gasdynamic expansion imposed on the reacting particles. Based on these calculations and the cell size measurements at critical conditions, a simple criterion for the sustenance of detonation was finally proposed. Simply stated, if a "stream tube" of particles entering the wavefront is subjected to an increase in cross-sectional area greater than 20% as these particles traverse the reaction zone (i.e., as they migrate one cell length behind the shock front), then the reaction zone will decouple from the leading shock and the detonation wave will fail. This simple premise was seen to hold true for all combinations of wall thickness and cell size under critical conditions. It was also demonstrated that the 10% velocity deficit observed near critical conditions by other investigators is a direct result of the 20% stream tube area increase.

A simple analysis was carried out to express the apparently universal criterion for self-sustained detonation in terms of diverging wavefronts. Details of the analysis are presented in the side panel, on p 67, for the interested reader. The results indicate that the critical radius for propagation of detonation in cylindrical geometry is $R_C^* = 4L_C$. In the case of spherical geometry, this radius is $R_S^* = 8.4L_C$. The larger value for spherical geometry is expected because the gasdynamic expansion for a given radius is more severe in spherical than cylindrical geometry. These values are the same as the observed critical radii in both the laboratory and field experiments on detonation transmission described earlier, thus giving further credence to the notion of a universal criterion for self-sustained detonation.

The above-described studies on the influence of boundary conditions on gaseous detonation provide one example of a fundamental contribution to the combustion field. In the years to follow, other significant contributions were made in related areas such as flame acceleration, deflagration to detonation transition, inhibition and quenching of detonation, chemical initiation of detonation, and multi-phase detonation phenomena. Many of these investigations led to practical applications. Some of these are described below.

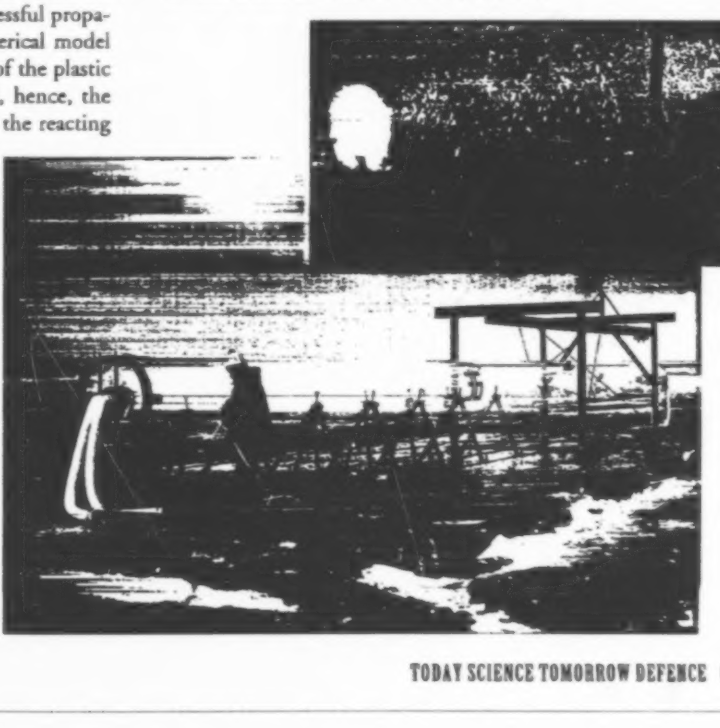


Figure 5: Photographs showing the large-scale apparatus used to investigate the influence of confinement on the propagation of detonation, and (inset) the detonation wave propagating in the bag. The gasdynamic expansion imposed on the wave was controlled by varying the thickness of the plastic bag wall.

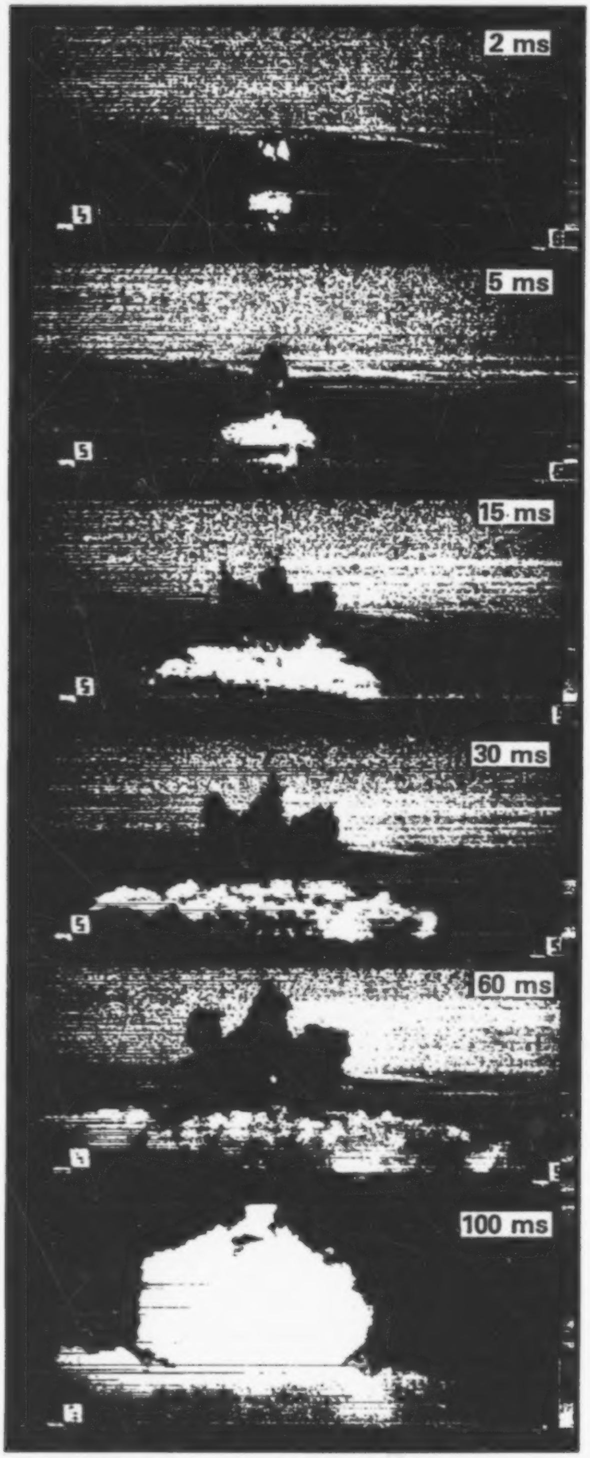


Figure 6: Selected frames from high-speed cinematographic records showing fuel dispersion and detonation of the droplet-air cloud formed by the JUGFAE device.

Military Applications of FAE Technology

One of the first opportunities to apply this technology to a scenario of military interest arose in 1983 when the British Army approached DRE Suffield for assistance in developing an inexpensive, reliable and expedient explosive procedure for clearing large minefields left on the Falklands Islands by the Argentine Army a year earlier. The British came to DRE Suffield because of its international reputation in the detonation field, and because the testing of large explosive devices was only possible in a few locations throughout the world.

A scheme involving large jugs of detonable hydrocarbon fuel was devised to meet this challenge, called "JUGFAE". Basically, it consists of a 50-liter plastic carboy filled with a suitable fuel and fitted with an axial fuel dispersal or "burster" charge. Detonation of the burster results in the fuel being driven radially outward to form a droplet-air cloud approximately 12 meters in diameter by 2 meters high. A "secondary" charge mounted on a post is detonated a fraction of a second later to bring about detonation of the cloud. Selected frames from a high-speed cinematographic sequence showing fuel dispersion and detonation are presented in Figure 6.

Detonation of a heterogeneous mixture such as a droplet-air cloud is not unlike the single-phase, gaseous phenomenon studied earlier. However, physical as well as chemical processes also play a role in determining the reaction rates. Important physical phenomena include droplet deformation and stripping, as well as atomization and evaporation of the liquid fuel. These additional phenomena are illustrated in the diagrams of Figure 7.

The JUGFAE device was not new to DRE Suffield. In view of Canada's difficulty in obtaining technical information about FAE from foreign sources, scientists had previously used such a device to simulate typical FAE warheads in their effort to assess the threat posed to the Canadian Forces. Consequently, numerous tests had already been conducted to optimize the cloud shape and size, to identify the optimum height of burst, and to determine the critical initiation requirements. Various fuels had also been tested for their suitability in such applications.

The large-scale clearing operation proposed for the Falklands involved placing a series of carefully spaced tripods in a row just inside one edge of a minefield using a crane. A JUGFAE device, complete with fuel and burster charge, would be suspended from the tripod at its optimum height of burst. A series of overlapping hemi-spherical clouds would then be created by the simultaneous detonation of all burster charges. Cloud detonation would be initiated by a single secondary charge positioned inside one of the end clouds. Having cleared a lane along one edge of the minefield, the crane would then advance one cloud diameter forward and the procedure would be repeated. This strip-wise procedure would continue until the entire minefield was cleared.

Although the effectiveness of FAE against Falklands-type mines was demonstrated in full-scale tests, and worries about the reliability of cloud-to-cloud transmission were put to rest, the JUGFAE clearing system was never fielded in the islands. This was because the high-priority minefields were located near populated town sites, and British authorities did not want to subject the residents to repeated blasts from fuel-air explosions in view of what they had just endured. Today, most of the minefields in the Falklands are as they were at the cessation of the conflict. The army has fenced and marked them, but appears to be awaiting advances in detection technology before revisiting the problem.

> *he Norwegian government was worried that underground military and civilian installations might be vulnerable to FAE.*

Based on DRE Suffield's reputation in the area of detonation transmission, and it's practical working knowledge of FAE warheads, it did not take very long before JUGFAE found another use, this time in a Canada/Norway collaboration. The Norwegian government, which has numerous underground military and civilian installations scattered throughout the country, was worried that these might be vulnerable to attack by FAE. Large installations are normally equipped with a ventilation system that draws in air from the outside. Given that a large FAE weapon has a significant time delay (several seconds) between fuel dispersal and detonation, there were concerns about the possibility that a detonation initiated outside the installation might find its way inside if conditions were favourable for its propagation.

Several concepts for protecting these structures were proposed and tested. Some of these attempted to quench the detonation wave at the entrance to the intake duct by subjecting it to gasdynamic cooling (e.g., expansion valves and orifice plates), while others focussed on destabilizing the wave by breaking it down into a series of small wavelets which were easier to quench (tube bundles). Still other approaches were based on inducing failure of the wave by extracting heat from it (water curtains and particle beds).

Another unique concept was to install deliberate ignition devices near the entrance of the duct. These devices took the form of heater coils or electronic units designed to provide a continuous spark source. The objective here is to ignite the fuel dispersed by the weapon before it is detonated by the secondary charge, thereby ensuring that only mild deflagration of the cloud is possible. Although the results of this collaboration are not in the public domain for obvious reasons, many Norwegian installations are today protected by equipment stemming from this study.

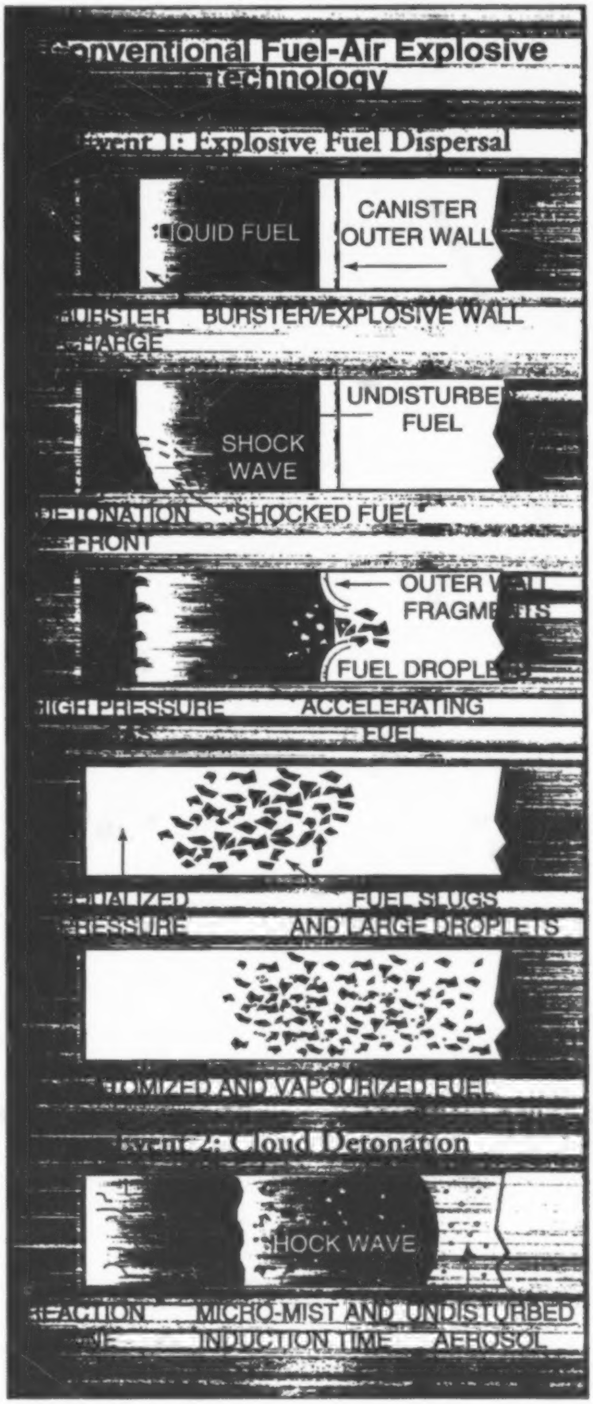

onventional Fuel-Air Explosive
Technology
vent 1: Explosive Fuel Dispersal
LIQUID FUEL
CANISTER
OUTER WALL
URSTER
HARGE
BURSTER/EXPLOSIVE WALL
UNDISTURBE
FUEL
SHOCK
WAVE
ETONATION
FRONT
SHOCKED FUEL
OUTER W
FRAGME
FUEL DROPLE
IGH PRESSURE
ACCELERATING
FUEL
UALIZED
RESSURE
FUEL SLUGS
AND LARGE DROPLETS
TOMIZED AND VAPOURIZED FUEL
vent 2: Cloud Detonation
SHOCK WAVE
EACTION
NE
MICRO-MIST AND
INDUCTION TIME
UNDISTURBED
AEROSOL

Figure 7: Schematic diagrams showing the complex physical processes which take place during explosive dispersion of a liquid fuel and the subsequent detonation of the resulting droplet-air cloud.

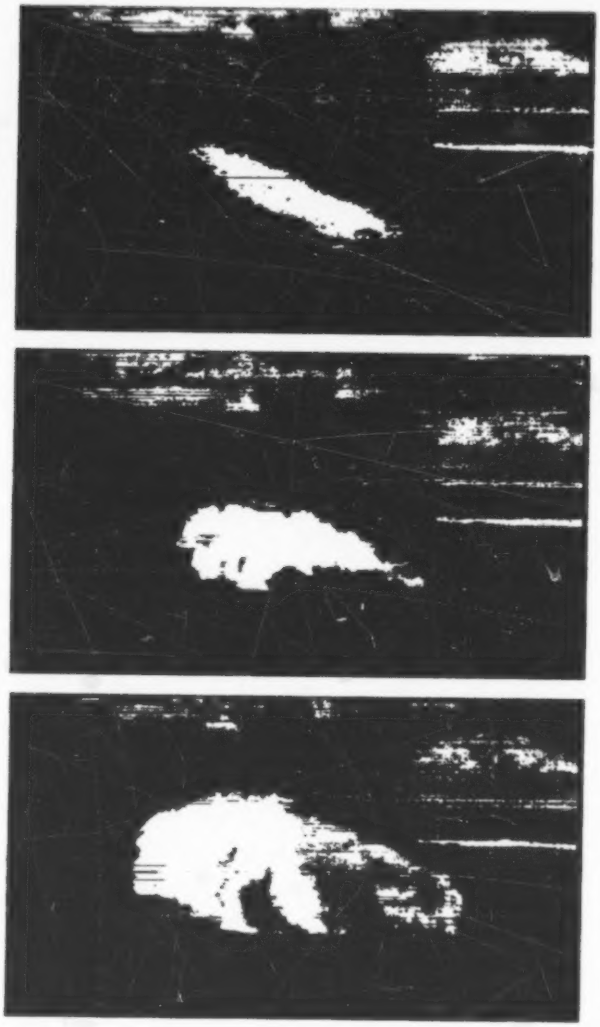


Figure 8: Selected frames from high-speed cinematography showing explosive fuel dispersion from a 200-meter long FAE line charge and detonation of the resulting droplet-air cloud.

The FAE program has proven to be of value to the Department with respect to evaluating and developing new military procedures and systems. On one such occasion, DRE Suffield was asked to assess an expedient demolition procedure which had been published in a popular foreign armed forces magazine. Because the assessment team was familiar not only with the fundamental science of the problem, but also the safety and operational constraints consistent with military operations, it recommended against adopting the procedure in Canada. Instead, a simpler explosive device employing agricultural dusts and commercially available items was promoted in its place. This device is capable of totally demolishing a steel-reinforced concrete bunker.

The best known equipment development project associated with the FAE program is the "Fuel-Air Line-Charge Ordnance Neutralizer," or FALCON minefield breaching system. This system is based on the FAE line-charge concept. The line charge consists of a hose filled with liquid hydrocarbon fuel. An internal burster charge is used to rupture the hose and disperse the fuel into a long fuel droplet-air cloud. In essence, the line charge is a JUGFAE device of smaller diameter and higher aspect ratio laying on the ground. Considerable design work went into the optimization of the line charge. For example, sophisticated computer programs were developed to model the blast field generated by the detonation of various fuel droplet-air clouds.

A sequence of high-speed film frames showing explosive fuel dispersion and subsequent detonation of a propylene oxide droplet-air cloud is shown in Figure 8. The cloud measures 2.5 meters high by 12 meters wide by 200 meters long. Detonation of the cloud results in a blast wave equivalent to that generated by some 5 tons of TNT. The blast is capable of either actuating or destroying surface-laid or shallow-buried, simple pressure-fuzed mines. DRE Suffield is the only location in Canada where explosions of this scale can be studied.

Once the line charge was perfected and a system concept devised, Canadian industry was contracted to build a functional Advanced Development Model (ADM) for demonstration purposes. During a typical breaching operation, a 300-meter long hose (containing only a burster charge) is first deployed over the mined area by a rocket-powered vehicle. Following deployment, high-pressure gas is used to drive fuel from a storage tank into the hose. Once the hose is approximately two thirds full, the gas is diverted to a second storage tank containing a water/antifreeze solution. The remainder of the hose is filled with this solution to provide a safe stand-off between personnel and the ensuing explosive event. Once the hose is filled, the cloud is formed and detonated to create a safe lane through the minefield. Rocket deployment of the hose is shown in Figure 9.

> *he probability of deflagration to detonation transition in a heavy water plant is very small.*

Although the ADM FALCON was demonstrated successfully during the autumn of 1991, the Department decided not to bring this equipment into service because the mine threat evolved significantly throughout the course of development. DRE Suffield has, instead, been given a mandate to develop enhanced-blast concepts which will be capable of defeating the hardened and complex-fuzed mines of tomorrow. And so, another step in the mine/countermine spiral begins.

Despite the Cold War coming to an end, the need to maintain a strong technology-base program in FAE has never

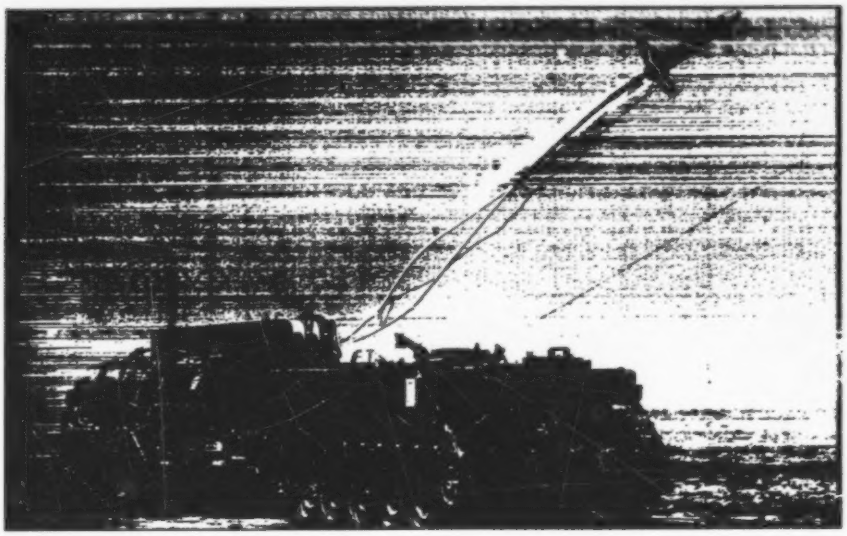


Figure 9: Photograph showing the rocket deployment of an empty line-charge hose by the FALCON minefield breaching system. The launch rail and line-charge storage magazine can be seen in the background, while the fuel and water/antifreeze storage tanks appear in the foreground.

been greater. Today, for example, Canadian peacekeepers are active in about a dozen hot spots throughout the world where they are being exposed to significant new threats. This point was emphasized recently when the intelligence community was able to identify a previously unknown weapon technology having high deployment potential in at least one Canadian Forces theatre of operations. In this instance, DRE Suffield was able to respond quickly to quantify the threat by manufacturing and testing replica warheads. A timely response was only possible because the expertise and facilities necessary to carry out such a threat assessment were already in place. Of course, the ultimate goal of such an undertaking is to devise countermeasures which can be implemented to minimize casualties and the loss of equipment.

Civilian Spin-offs of the Technology

Although the knowledge base, instrumentation capabilities, and numerical modelling skills which accrued at DRE Suffield were in direct support of military requirements, these resources have been applied to problems of loss prevention in Canadian industry as well.

DRE Suffield was able to assist industry on one occasion when the Atomic Energy Control Board (AECB) expressed concerns about the possibility of an accidental explosion in heavy water production facilities. One of the by-products of heavy water processing is hydrogen sulphide gas. Very little was known about its detonability. An accidental release of combustible gas in a heavy water plant is of particular concern because such a facility contains a maze of pipe racks and processing vessels. Recall from an earlier section that these are precisely the conditions necessary to accelerate a mild flame to velocities where deflagration to detonation transition (DDT) can occur.

In order to address this concern, DRE Suffield carried out critical tube diameter tests to assess the detonation sensitivity of hydrogen sulphide-air mixtures relative to other more common fuel-air mixtures. Experiments were also carried out in large rectilinear plastic bags containing arrays of pipes deemed to be typical of those found in a heavy water plant. In these experiments, the combustible gas was ignited at one end of the array, and the resulting flame was monitored to observe whether or not DDT would occur. Although hydrogen sulphide was the gas of interest, tests were also conducted using acetylene-air and propane-air mixtures as familiar benchmarks. Figure 10 shows the transition taking place in a mixture of acetylene-air. Fortunately, the detonation sensitivity of hydrogen sulphide-air mixtures was found to be quite low and scientists were able to report that the probability of DDT taking place in a heavy water production plant was very small. Had the findings been different, they would have

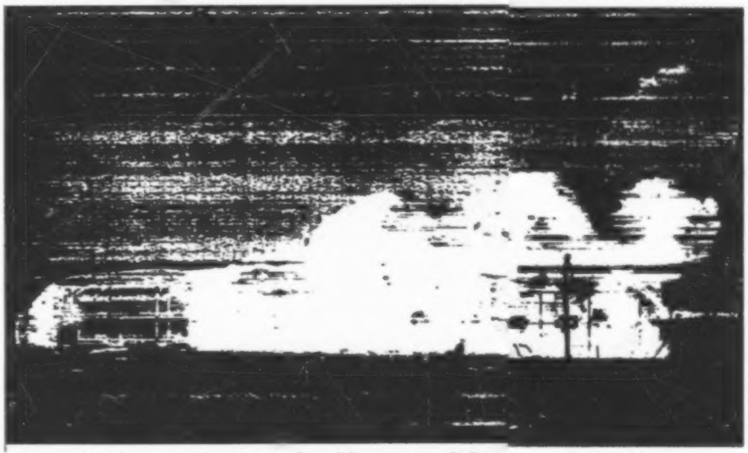


Figure 10: Flame acceleration induced by a series of obstacles resulted in deflagration to detonation transition (DDT) in this test involving acetylene-air. Fortunately, DDT was not observed in mixtures of hydrogen sulphide and air, the most likely mixture to be involved in an accidental explosion scenario in heavy water plants.

had serious implications with respect to the design of future facilities.

Another example of the value of the FAE program to Canadian industry is the DRE Suffield contribution to the understanding of hazards associated with pipeline ruptures. Novacor, an Alberta based pipeline utility, was concerned about the possibility of DDT taking place following the rupture of a pipeline containing high-pressure ethylene gas. Most gases transported by pipeline are relatively insensitive to detonation. It is standard procedure for emergency response crews to position themselves upwind of the rupture and to ignite the combustible cloud using a flare in order to prevent the cloud from growing to dangerous proportions.

The situation is somewhat different with ethylene because it is one of the more detonation sensitive gases in the hydrocarbon family. The question arose as to whether the standard flaring procedure was really a wise idea. To answer this question, an experimental investigation was initiated in which a pipeline rupture was simulated on a small scale by a nozzle issuing ethylene gas. The experiments were conducted in large plastic bag structures about the size of a typical house to minimize the effects of ambient winds on the formation of the combustible clouds. Numerous tests in which the clouds were ignited at different locations failed to reveal conditions under which DDT would occur in an unconfined cloud.

> *s a result of this investigation, the pipeline industry is now reviewing its emergency procedures.*

Based on their comprehensive knowledge of flame acceleration and DDT, however, scientists were convinced that transition to detonation could be induced in ethylene-air mixtures under relatively common conditions. Along these lines, an experiment was proposed in which a 0.5-meter diameter agricultural drainage pipe was filled with ethylene-air and ignited at one end. Such pipes are routinely installed under highways. Tests confirmed that DDT could occur inside the pipe if either the ignition end was partially blocked or a series of small boulders was positioned inside the pipe far away from the ignition source. The worrisome consequence of these findings is that the critical diameter for stoichiometric ethylene-air is only 0.43 meters. This means that the resulting detonation in the pipe will be capable of exiting the pipe and causing detonation of the bulk of the combustible cloud. As a result of this investigation, the pipeline industry is now reviewing its emergency response procedures.

A third example of how the expertise in the FAE program has been of value to industry was the assistance provided to Westech Industrial Limited, a Calgary-based manufacturer of large flame and detonation arrestors. One sector of the flame arrestor market deals with tanker loading facilities at large international ports. In the past, it was acceptable for a tanker to simply vent its hull vapours to the atmosphere while taking on a cargo of liquid hydrocarbons. Today, environmental laws prohibit this practice. The hull vapours must now be piped hundreds of meters to an incinerator and burned off. Needless to say, a pipe filled with combustible vapours poses a potential hazard when there is a flame at one end of the pipe and a ship at the other. The purpose of a flame arrestor is to prevent a combustion wave from propagating back to the ship.

Westech Industrial used in-house R&D resources to develop a world-class 45-cm in-line flame arrestor which became the first to gain United States Coast Guard approval for use at tanker loading facilities. Westech's American competitors were not very happy about this development, so they proceeded to hire some of the best consultants in the combustion field to discredit the Westech design. The competitors claimed that the arrestor would not survive at the end of a 300-meter long pipe due to the high momentum of the gases inside the pipe during detonation. This is where DRE Suffield and its contractors entered the picture. After listening to the competitors' allegations, scientists analyzed the problem and concluded that the claims were likely false. However, as is the case with so many other problems in combustion, insufficient knowledge was available to refute the claims outright. It was also concluded that results from scaled down tests would not stand up to expert scrutiny. Therefore, scientists recommended that Westech build a 300-meter long detonation tube (the longest one in the world) in order to demonstrate the survival of its product.

This endeavour turned out to be quite a success story. The company has put to rest the adverse claims against its arrestor and has thus retained its share of the $50M annual flame arrestor market. The involvement of combustion experts in the project also resulted in changes to the certification procedures for flame arrestors throughout the world. Previously, it was believed that detonation conditions posed the most severe test for flame arrestors. It is now known that DDT at the entrance to the arrestor is the most serious scenario.

The Way Ahead: Improvements and New Directions

Military requirements are constantly evolving as the world political situation changes and technology advances by leaps and bounds. This means that defence scientists are presented with the ongoing challenge of keeping abreast of relevant technology advances and, in many cases, branching into new technology areas.

The DRE Suffield work in explosive minefield breaching is an example of this dynamic process. Ten years ago, the major focus was on the use of FAE to neutralize simple pressure-fuzed mines because this mine type accounted for a large proportion of the global inventory of mines. This is no longer the case.

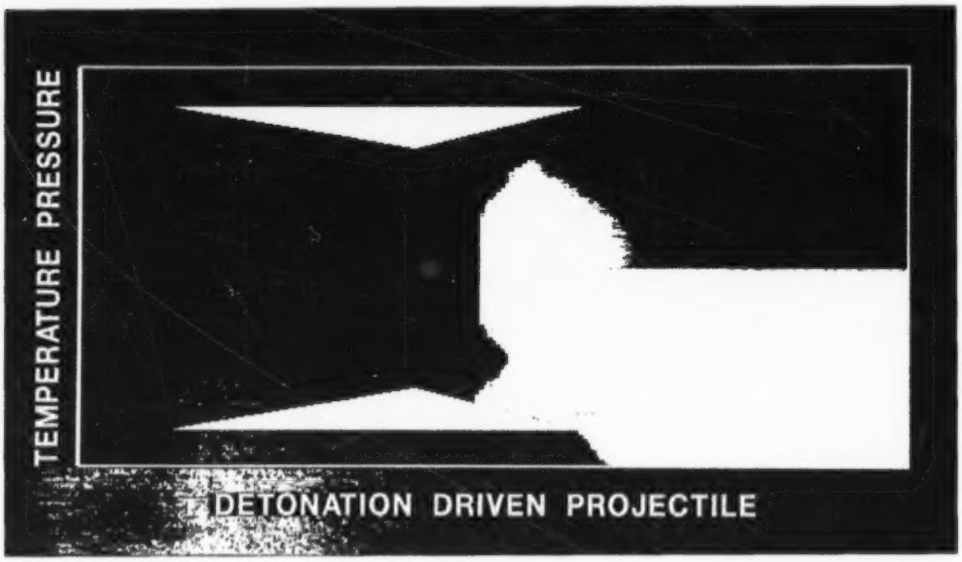


Figure 11: Results of computer modelling showing the complex wave structure inside a proposed detonation driven engine. The engine consists of a converging inlet, a throat, and a diverging nozzle. This engine is capable of flight in the Mach 7 range.

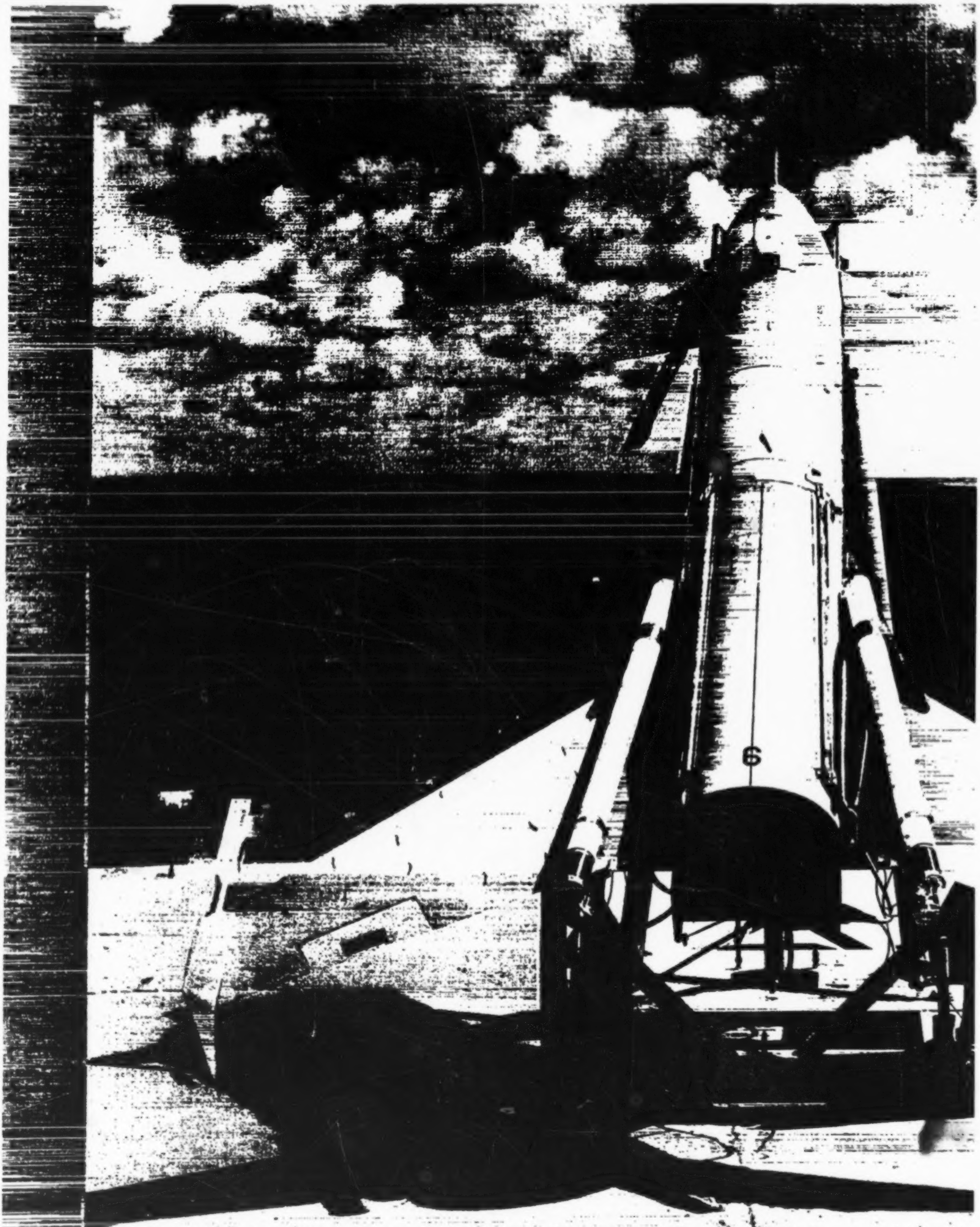
Most mines produced today are immune to the level of blast generated by FAE. Consequently, new explosive approaches capable of generating much higher pressures are being assessed for their ability to defeat hardened mines. Some of these are considerably different from FAE. They include explosive foams which have the consistency of shaving cream, dispersed explosive dusts and liquids, shaped charges, explosively formed projectiles, high-explosive line charges, and a phenomenon known as in-ground explosion that involves the detonation of a liquid-explosive saturated soil.

New and exciting aspects of FAE are also being explored for their potential in future military applications. One such avenue of pursuit involves a device known as a "detonation driven engine." The in-depth understanding of detonation phenomena, coupled with the predictive capability made possible by the computational tools developed at DRE Suffield, have enabled scientists to design an engine with no moving parts that is capable of flight near Mach 7. The engine literally rides a detonation wave in the same manner that a surfer rides a wave of water. Figure 11 is a computer animation image showing the detonation wave stabilized in the throat of the engine. This device could become the basis of a new generation of horizontally fired mines, a demolition device capable of cutting structural members from a distance, an armour piercing round, or perhaps even a high-speed propulsion system capable of launching payloads into space. The applications of this and other technologies are limited only by the imagination and creativity of the individual researchers.

Acknowledgements

The success of the FAE program is a reflection of the dedication and professionalism of the many scientists, engineers and technologists who have worked in the program over the years. These include Ingar Moen, Paul Thibault, John Lee, Rom Knystautas, Simon Labbé, Keith Gerrard, Chris Brosinsky, Steve Ward, John Funk, Gayle Hall, and Linda Beaupré. Appreciation is also extended to members of the Photo Group, Electronic Design and Instrumentation Group, the Hazardous Materials Group and the Field Operations Section for their high level of support.

Corporate thanks are due to Combustion Dynamics Limited, McGill University, Brome Laboratories Inc., Mining Resource Engineering Limited, Thomson-CSF Systems Canada Inc., and TES Limited.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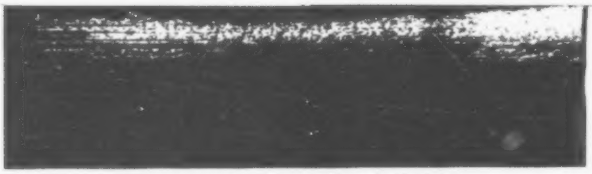
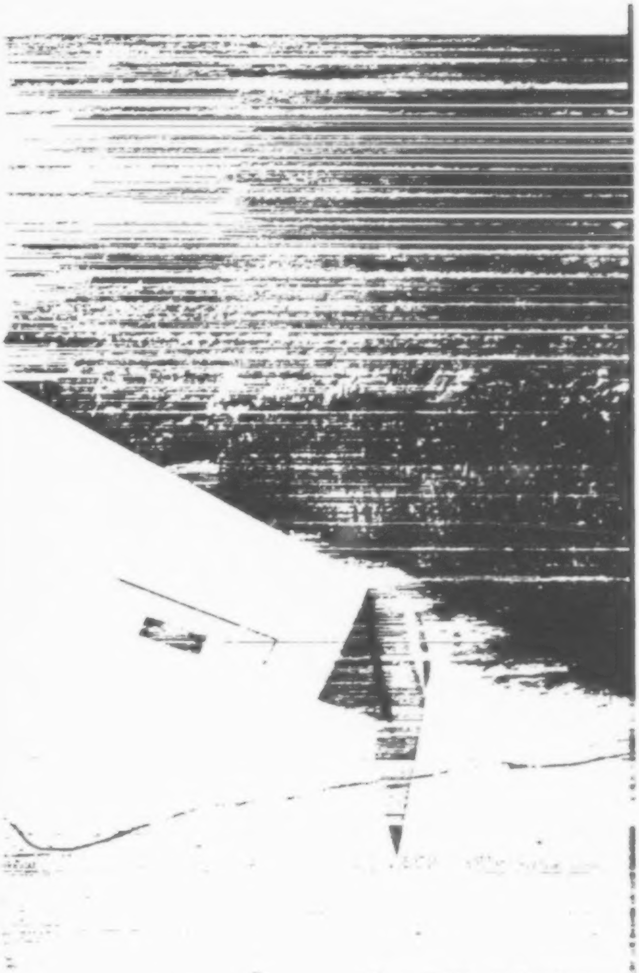


AERIAL TARGETS

Defence and training against sophisticated missile attacks requires equally sophisticated aerial targets



by A.B. Markov,
Herring and C.G. Coffey

With the major geopolitical changes occurring in Eastern Europe and other parts of the world, the Canadian Forces (CF) must be ready to conduct operations, frequently on short notice, in virtually any part of the world. To prepare for such action requires the continual training of personnel involved in all aspects of modern military operations, the ongoing assessment and improvement of in-service military systems, and the assessment of new systems under consideration for procurement.

Aerial targets are one important element of a host of training and weapon performance monitoring tools available to the CF for exercising various defensive weapon systems. They are required in support of training and effectiveness assessment for a variety of guided and unguided weapons spanning a broad performance range. The availability of cost-effective targets in Canada is essential to maintaining a high level of readiness in the CF, to permitting less expensive training and weapon performance monitoring exercises in Canada (versus the conduct of such operations on foreign ranges), and to supporting a Canadian aerial target development capability in industry.

At Defence Research Establishment (DRE) Suffield, scientists and technologists have been at work developing cost-effective aerial target and weapon performance monitoring technologies for all three elements of the CF. Over the years, experimental facilities have been established that permit the cost-effective development and assessment of these technologies. In many instances, these facilities have been made possible only due to the availability of the DRE Suffield Experimental Proving Ground (EPG). This area of Canadian Forces Base Suffield, dedicated to DRE Suffield and industry research and development activities, is uniquely positioned for the conduct of a variety of development activities including aerial targets.

The targets research has culminated in the successful development of a number of proof-of-concept target systems, the transfer of the resulting systems to industry for further development, the development of a capability for conducting both training and weapon performance monitoring in Canada, facilitation of a Canadian industrial capability that is able to support future CF requirements as well as to compete in export markets, and the development of a variety of EPG facilities for the integration and flight testing of aerial targets.

EVOLUTION OF CAPABILITIES

The successes of the targets research and the development of state-of-the-art integration and test facilities did not happen overnight. Rather, they are a result of a longer term DND investment in the capabilities of the EPG and in the development of increasingly more sophisticated target systems.

The roots of the aerial targets research go as far back as the early 1970's when scientists and technologists at the DRE Suffield recognized a growing requirement within the CF for more sophisticated aerial target technologies than were then available. This awareness came as a result of work that was being conducted with the Canadian Navy in commissioning the anti-air self-defence capability of the new DDH 280 class of destroyer, including the Sea Sparrow surface-to-air missile and a five inch radar controlled gun system. The work with the DDH 280 surface-to-air weapon systems was invaluable in providing the system-level knowledge essential to effectively address the associated aerial target technology requirements.

Experimental Proving Ground ... dedicated to DRE Sufffield and industry research and development activities, is uniquely positioned for the conduct of a variety of development activities including aerial targets

This was particularly true in the sense of giving DRE Suffield scientific and technical staff insight into upcoming requirements, so as to anticipate long-term technology requirements that would be essential to meet aerial target needs in future CF surface-to-air weapon system procurement.

The initial aerial target technology R&D work at DRE Suffield focused on gaining a better understanding of the existing aerial target technologies, techniques and systems. As the work progressed, a multidisciplinary research group evolved with expertise in the integration of diverse technologies such as flight dynamics, aerodynamics, guidance and control, navigation, propulsion, flight test data acquisition, reduction and analysis, IR and radar augmentation, and miss distance measurement. This integration capability has frequently been put to use not only in the targets and weapon performance areas, but also in the integration and deployment of systems as diverse as the Mobile Atmospheric Sampling and Identification Facility (MASIF, see companion paper "Field Detection and Identification of Biological Warfare Agents" in this publication).

During this initial period a number of modest R&D efforts were undertaken that addressed several CF aerial target requirements and at the same time provided hands-on experience for DRE Suffield staff. These efforts included development of an aircraft-towed target named MILKCAN for DDH 280 five inch gun firings, and a number of system improvements to an existing low-speed propeller-driven Army target developed by Targetair Inc. in Moncton, New Brunswick and referred to as the TATS 102.

These early efforts also made DRE Suffield staff aware of the system problems associated with providing good aerial targets. Most notably, these problems included providing accurate miss distance measurements and of providing sub-scale targets that have representative visual, radar and IR signatures. Early remotely piloted vehicle research and exploratory development trials conducted on the DRE Suffield EPG also demonstrated a growing requirement for more sophisticated data acquisition, reduction and analysis capabilities.

The work on rocket boosted aerial targets also had its start in the late seventies. At that time a collaborative effort was initiated under the auspices of the Aerial Targets and Drones (Technical Panel H-1) of The Technical Cooperation Program (TTCP)[1]. This effort was based on a US Army/DRE Suffield agreement to take a US Army rocket-boosted target system referred to as BATS (Ballistic Aerial Target System), and modify it for use with the Canadian-developed C14 (CRV-7) 70 mm rocket motor. This effort ultimately led to an all CRV-7 powered aerial target that became known as ROBOT-9 (ROcket BOosted Target). The new name reflected both the fact that it was substantially a new system with capabilities that BATS did not have and that the design, prototyping and testing had been done in Canada. Working with the Naval Engineering Unit Atlantic (NEUA), Maritime Command (MARCOM), and the Directorate of Maritime Combat Systems (DMCS) in National Defence Headquarters, a series of technical and operational evaluations were conducted of the ROBOT-9 system in the early 1980's. This led to the acceptance of the ROBOT-9 system by the Canadian Navy as an aerial target system suitable for up to Mach 1.3 presentations to the Sea Sparrow surface-to-air missile system.

ROBOT-9 system is a free flight... uncontrolled vehicle, its low cost, high speed, known radar cross-section and relative ease of deployment and operation made it an attractive system in many scenarios.

Although the ROBOT-9 system is a free flight, uncontrolled, essentially ballistic flight vehicle, its low cost, high speed, known radar cross-section and relative ease of deployment and operation made it an attractive system in many scenarios. These scenarios include operator training and postrefit fire control radar check-out and qualification. More importantly, exercises could be conducted in local Canadian waters without the requirement for foreign range aerial target services. The latter is proving to be an ongoing consideration in planning Canadian naval evaluation and training exercises associated with the Canadian Patrol Frigate (CPF), and the Tribal Class Update and Modernization Program (TRUMP), as well as future naval procurements.

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[1] *The TTCP provides a mechanism for Australia, Canada, United States, United Kingdom, and New Zealand to conduct cooperative research programs in technical areas of mutual interest concerned with broad areas of defence research. The goal of TTCP is to identify areas of common research interest and to provide recommendations for new R&D activities.*

As is the normal practice within the Defence Research Establishments, in the course of this effort DRE Suffield transferred the technology associated with the ROBOT-9 system to the Canadian Navy and to Canadian industry. Bristol Aerospace Limited (BAL, Winnipeg) has been licensed by DND to supply ROBOT-9 to the Canadian Forces and to any off-shore customers that can be identified.

ROBOT-X DEVELOPMENT

The technical success of the ROBOT-9 system, in conjunction with its cost-effectiveness, suggested that a maneuvering, rocket-boosted target flying under autopilot and/or ground control would provide a number of advantages over turbine-powered targets of equivalent performance. At the same time, some of the inherent limitations and disadvantages of the ROBOT-9 approach (e.g., inability to maneuver and ranges shorter than naval over-the-radar horizon ranges) could be eliminated.

DRE Suffield involvement with what eventually became known as ROBOT-X (the 'X' is a common aerospace acronym for experimental) commenced in 1981 with a feasibility study addressing the number of CRV-7 rocket motors that would be required for 37 km (20 nm) ranges at subsonic velocities. This requirement stemmed from the focal objective of developing cost-effective technologies that could be applied towards the development of a naval point defence missile system target. This target would simulate a low flying subsonic invader aircraft or a low-flying subsonic antiship missile coming from beyond the radar horizon. Even in this conceptual stage, it was recognized that development of these technologies and any associated flight vehicle would have a high degree of potential in air-to-air and low-level air defence applications.

In parallel with this feasibility study, consideration was given to other aspects of the system that would have to be addressed in order to provide a cost-effective, relatively high performance system. The criteria that evolved in 1981-82 can be best summarized as follows:

- The development of a proof-of-concept (POC) flight vehicle to modest requirements and specifications was essential. The design to manned aircraft standards or to military specifications associated with weapon system development was to be avoided wherever possible, within the general proviso that neither safety nor the ability to achieve the basic performance objectives would be compromised.
- The single most critical technology element was that of cost-effective guidance and control. All initial efforts in this area focused on developing a guidance and control methodology that is "fire and forget", i.e., the flight vehicle would have a preprogrammed/autonomous guidance and control system. This effectively eliminates a very significant component of the cost of the airborne system and associated ground support equipment.
- To achieve cost-effectiveness, emphasis was placed on relatively low-cost guidance and control hardware in conjunction with sophisticated software. This approach took advantage of the hardware revolution in microcomputer electronics and allowed for the successful implementation of novel algorithms utilizing inertial sensors of modest performance and cost fixed to the vehicle for the estimation of vehicle attitude (pitch, roll) and heading angles, referred to as strapdown attitude and heading reference system (AHRS) algorithms.
- The POC flight vehicle would have a relatively low-cost airframe through the use of a geometrically simple configuration and the selection and use of materials and production techniques that provide low cost airframes in modest volumes.
- It was recognized that system and technology integration issues are fundamental in their own right and must be addressed early in a research effort. This recognition led to a system integration awareness throughout the ROBOT-X POC project, and resulted in an emphasis on system robustness and relative ease of operation that continues to pay dividends to this date.

The emphasis on a cost-effective and operationally-effective system did not, of course, imply a trivial R&D effort. Indeed, the converse was the case–there was an extensive requirement for designing, prototyping and testing of virtually all subsystems from first principles in order to achieve the desired mix of good performance with low cost.

Following the preliminary work of 1981-82, the technical leadership, planning, direction and implementation of both the POC flight vehicle and the associated ground systems for the ROBOT-X POC project were conducted within DRE Suffield. This part of the development took the effort through four phases that culminated in the completion of exploratory development and associated flight testing. These phases were as follows:

- Feasibility Study.
- Configuration Design.
- Detailed Airframe and Avionics Design.
- Proof-of-Concept Flight Testing.

The primary objectives of this effort were to enable the technologies essential to allow a maneuvering, high subsonic speed aerial target using 70 mm rocket motors as its basic propulsion unit to meet its basic performance objectives, and, most importantly, to provide the basis for a design to do this in a cost effective way.

ROBOT-X Proof-of-Concept Flight 3 Launch (29 August 1986) - The POC flight series consisted of a total of 17 flights conducted by DRE Suffield on the Experimental Proving Ground. The flights accumulated over 37 minutes of flight time in highly instrumented flight vehicles utilizing a variety of data collection techniques (video, telemetry, and radar), and demonstrated not only the rocket-boosted concept but also a number of technologies key to providing a cost-effective aerial target.

One of the roles of the DRE Suffield ROBOT-X project team was to coordinate the efforts of DRE Suffield with other DND agencies and directorates, other federal government agencies, Canadian universities and private industry. The resulting multi-disciplinary team included members from all of these organizations, and ultimately fostered the transfer of the technology to industry and the development of a Canadian industrial target development capability.

The POC project resulted in a flight vehicle and associated technologies that is uniquely Canadian, and has developed a Canadian base in cost-effective subscale aerial target technologies and unmanned vehicle guidance and control technologies. The effort culminated in a seventeen flight POC flight test program that included:

- Demonstration of all basic flight vehicle performance requirements, including the ability to achieve greater than 20 nm (37 km) flight ranges and flight speeds up to Mach 0.9.
- Development of a robust airframe that has 8g structural capability in a symmetrical, geometrically simple canard configuration (controlled maneuvering flight up to 5.0g was demonstrated).

ROBOT-X TECHNOLOGY TRANSFER

The ROBOT-X proof-of-concept (POC) work with industry was conducted with two specific objectives. The first of these was to access the expertise and facilities not readily available within government laboratories and required to take ROBOT-X from concept through POC flight trials; the second, and more fundamental objective, was to involve Canadian industry in ROBOT-X development at a sufficiently early stage to facilitate the technology transfer process.

The POC effort led to a seven million dollar Advanced Engineering Development (AED) project managed from National Defence Headquarters (NDHQ), and contracted with Bristol Aerospace Limited*. This effort was focused specifically on providing a fully integrated aerial target for Canadian naval use. It has addressed a number of development issues including full transfer of the technology base to Canadian industry, system value engineering and development of maritime operational procedures for the aerial target configuration.

Phase 2 of the AED effort was completed in 1990 and included an initial series of firings at sea in May 1988 as well as a follow-on series of firings at CARIBOPS'89 in February 1989. Based on the results of Phase 2 and in part on the results of these firings, Phase 3 work was initiated in 1990 to take the system into production as a Canadian antiship missile aerial target. Phase 3 has now been completed with this target system in service for Canadian maritime target operations. More importantly, the technology and expertise transferred is now resident in industry, and is available for the pursuit of export markets.

The ROBOT-X effort has resulted in a considerable Canadian industrial participation at the R&D level, and has produced direct technology transfer to Bristol Aerospace Limited (BAL), which is licensed for the ROBOT-X aerial target technology, and to Atlantis Aerospace Corporation, which is licensed for the MicroPilot guidance and control technology. Both companies are pursuing off-shore markets for these systems and technologies. A Canadian aerial target technology base and industrial capability has been established.

**This work was initiated with Boeing Canada Technology Limited (Winnipeg). In 1992, however, Boeing Canada sold its aerial targets development work to Bristol, including ROBOT-X AED work.*

- Development of a cost-effective flight control technology in the form of an autopilot named MicroPilot, using a fly-by-wire architecture (all control surfaces and their associated electro-mechanical actuators are individually controlled by electrical command from the flight computer) and a number of embedded processors.
- Development of robust strapdown attitude and heading reference system (AHRS) algorithms that function effectively with inertial sensors of modest performance and cost.
- Development of an instrumentation suite that includes a high accuracy modular instrumentation signal conditioning subset, onboard real-time colour video, and a pulse-code modulation telemetry data stream capable of bit rates exceeding 250,000 bits/second and configured for up to 64 channels of telemetry with a mixture of analog and digital signals.

The ROBOT-X POC project resulted in a flight vehicle and associated technologies that are uniquely Canadian, and has developed a Canadian base in cost-effective subscale aerial target technologies and unmanned vehicle guidance and control technologies.

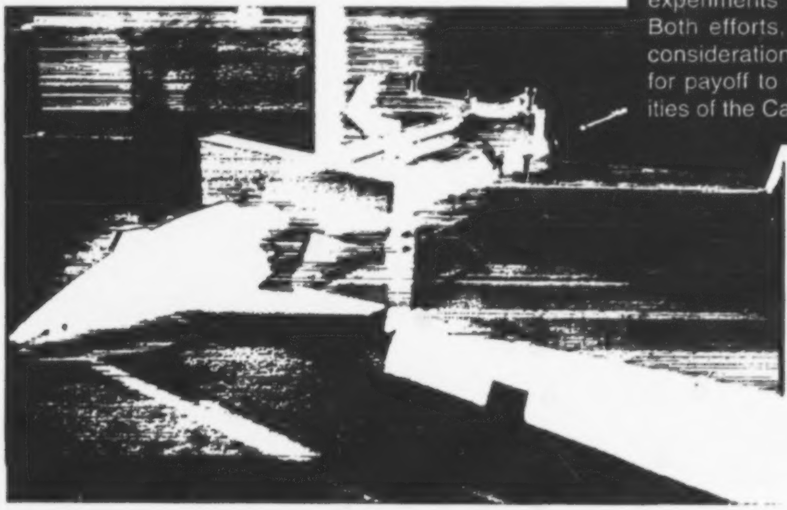
- Accumulation of an extensive data base that includes aerodynamic data from three series of primary wind-tunnel tests conducted in the five-foot blowdown tunnel of the Institute for Aerospace Research, Ottawa; environmental tests conducted at the Aerospace Engineering Test Establishment, Cold Lake; and a flight-test data base that includes both numerous test hours of the primary avionics in captive flight on a research aircraft as well as over 37 minutes of flight vehicle test time accumulated in the course of the seventeen POC test flights.

HATT-X TECHNOLOGY DEMONSTRATOR

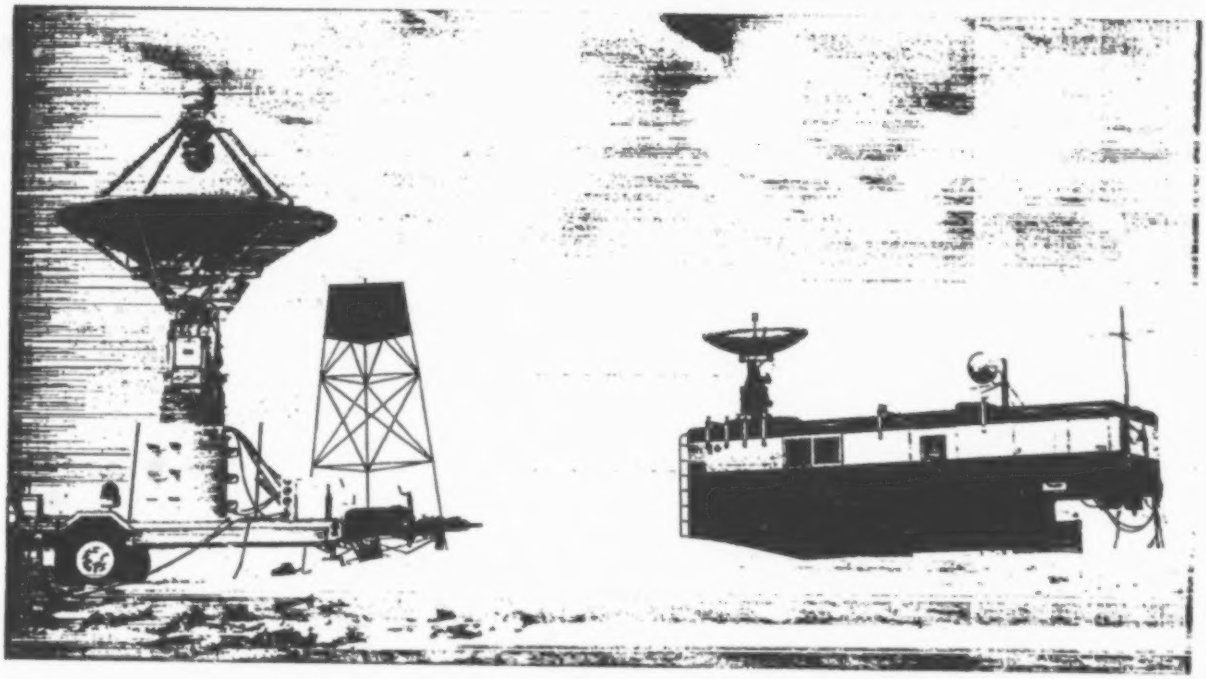
While the proof-of-concept ROBOT-X development and other aerial targets research were instrumental in establishing a Canadian industrial capability in subsonic aerial targets, current and future research facilitated by the availability of HATT-X will help maintain a competitive technology base in industry for future target requirements, and, more broadly, in land and airborne robotic systems. This work is fostered by the DRE Suffield Experimental Proving Ground with its established integration and data acquisition facilities, and the availability of the flight proven airborne platform.

HATT-X provides a unique, cost-effective flight vehicle that is able to carry significant scientific payloads for flight times exceeding 30 minutes, altitudes exceeding 9,150 m (30,000 ft) and speeds exceeding Mach 0.8. The exploration and development of systems that would otherwise have to be tested in more expensive or less available environments (such as manned aircraft), or could not be considered at all, has been facilitated.

The HATT-X effort has already resulted in a considerable Canadian industrial participation at the applied research level, and has stimulated a number of unique industry/DND research initiatives. Included among these is consideration of the application of neural network technologies to flight vehicle control (with the Australian Defence and Science Technology Organization and Atlantis Aerospace Corporation) and consideration of the utilization of HATT-X in the conduct of microgravity experiments (with ATS Aerospace Inc., Montreal). Both efforts, still in the early stages of scientific consideration, have significant long-term potential for payoff to Canadian industry and to the capabilities of the Canadian Forces.



HATT-X/ROBOT-X 20% WIND TUNNEL MODEL undergoing testing at the trisonic, 5ft. blowdown tunnel facility of the High Speed Aerodynamics Laboratory (Institute for Aerospace Research) of the NRC (Ottawa, Ontario).



Data Acquisition Centre has the capability for recording as well as presenting in real time a variety of telemetry, video and radar data provided in a number of formats. Included in this capability is the ability to monitor data arriving from remote sites including remote telemetry receiving sites such as that located at Trig 5 Telemetry on the DRE Suffield Experimental Proving Ground (EPG)

In part due to the requirements associated with ROBOT-X POC flight trials, DRE Suffield developed in the course of this project an extensive capability in instrumentation, video and telemetry which can facilitate a variety of research flight trials. This capability has subsequently been used for a number of unmanned aircraft and surface-to-air missile trials both in support of ongoing DRE Suffield R&D as well as Canadian Forces development and Project Office activities.

HATT-X

Although the ROBOT-X POC effort led to the establishment of a technology base suitable for meeting a number of current Canadian Forces aerial target requirements, the longer term research and technology benefits have also been very significant. The latter have included progress in the areas of cost-effective drone flight control technologies, cost effective airframes and the use of the CRV-7 in a controlled, winged flight vehicle. The establishment of research and range facilities at DRE Suffield suitable for a variety of future research and development programs is also proving to be of long term value.

A significant portion of the ROBOT-X POC flight vehicle assets remain, and have been phased into ongoing unmanned aerial vehicle R&D as advanced flying laboratories. This is a unique Canadian capability, and has been utilized in the past to advance flight vehicle technologies e.g., as per the NASA HiMAT program.

The flying laboratory version of ROBOT-X, referred to as a High-Speed Aeronautics Technology Testbed (HATT-X) is being transformed into a number of configurations that facilitate its research mission (see box on page 80). This effort is intended to make HATT-X into an agile, multi-mission flight vehicle that will allow DRE Suffield to fully address a number of research problems. It is a cost-effective flight platform that provides a unique capability for not only exploring emerging technologies in simulation and in the laboratory , but also in flight. As importantly, this asset (and the associated range data acquisition instrumentation) is available for use by other DND research establishments and by the CF in support of ongoing R&D efforts.

Current DRE Suffield aerial target research interests include advanced guidance and control architectures and techniques, very agile flight vehicles, emerging inertial sensor technologies and supersonic (Mach 2 plus) aerial target technologies. Although HATT-X cannot cover all of the speed and agility envelopes that are of interest, it provides a stepping stone towards achieving these longer term goals.

BEYOND AERIAL TARGETS

Aerial target technology has been developed to the proof of concept stage. A number of configurations of the HATT-X test bed provide the base for future research.

As is the case for many technology areas, it is not a simple task to anticipate the longer term (10 to 15 year) requirements for aerial target technologies, and, indeed, for "robotic" land and air military systems. A review of the current and anticipated requirements, however, suggests not only that future missile threats confronting the CF will be faster, more intelligent and have significant evasive capability, but that there will be many mission requirements that are best addressed with unmanned remotely controlled or autonomous systems (in both the land and air elements).

The aerial targets R&D is accordingly being redirected at addressing broader technological problems that build on the significant technology and system integration expertise that has been developed at DRE Suffield. In this way, requirements as diverse as providing technologies for fast (Mach 2+), highly maneuverable flight platforms and the detection of biological warfare agents may be addressed by the same multi-disciplinary integration team.

As a result, a number of efforts have been initiated for which the technology payoff is expected to be significant, including: the feasibility of utilizing neural network techniques for vehicular control, the feasibility of ground-based and airborne detection of metallic and nonmetallic mines, and the feasibility of a supersonic flying laboratory configuration (SUPER-X). The capabilities of the latter will include speeds in excess of Mach 2 with flight times of 90 seconds and an "intelligent", fully autonomous flight control architecture with a high-g maneuver capability. The potential technology benefits are very high for both DND and Canadian industry and the effort is consistent with anticipated CF requirements; as well, it builds on the experience and facilities already available.

> **his effort is intended to make HATT-X into an agile, multi-mission flight vehicle a cost-effective platform that provides a unique capability for not only exploring emerging technologies in simulation and in the laboratory, but also in flight.**

The DRE Suffield robotic technologies R&D effort continues to be conducted in concert with Canadian universities, industry, the National Research Council and a number of provincial research organizations, and will continue to provide the base necessary to meet the long term technology requirements of the Canadian Forces. The work will also provide essential technology and data to maintain Canadian industrial competitiveness in the increasingly difficult off-shore markets.

HATT-X CONFIGURATIONS

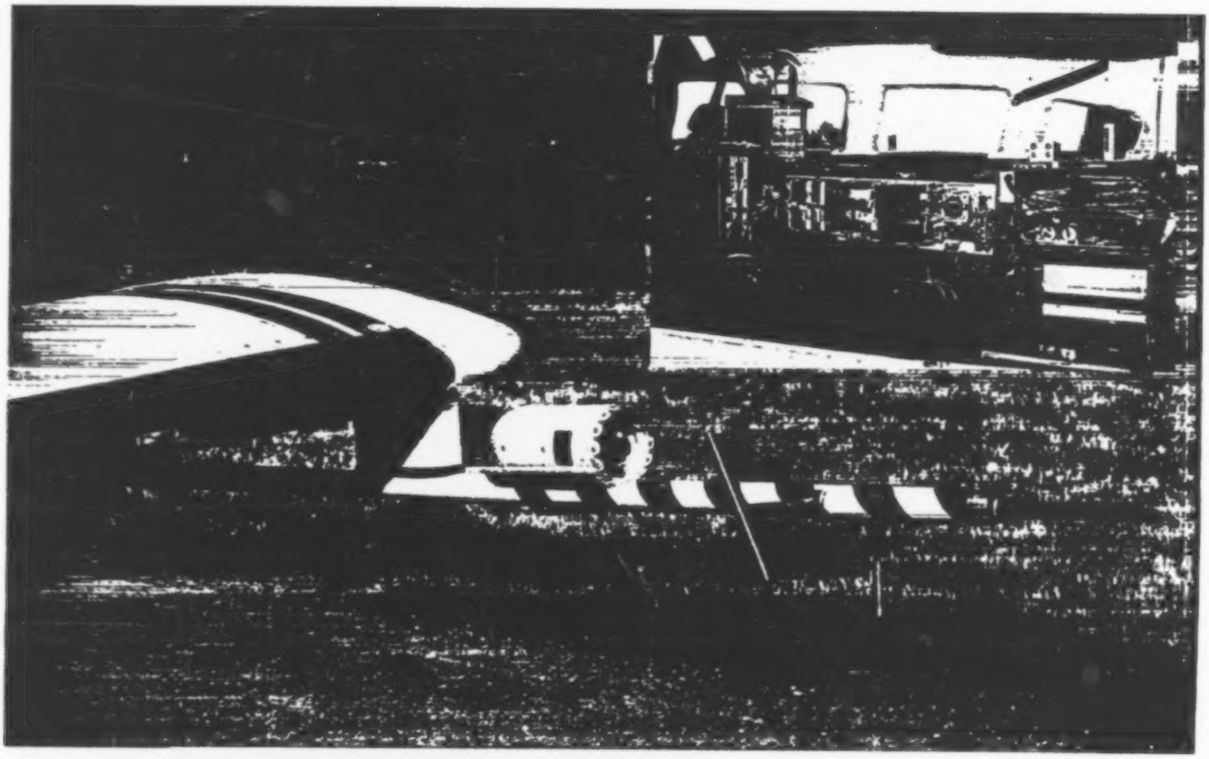
A number of HATT-X configurations are currently in place or are expected to be available in the near future. These include the following:

HATT-X Rocket-Boosted Configuration - This configuration utilizes up to 23 CRV-7 rocket motors fired in stages, and is similar to the rocket-boosted aerial target configuration. This configuration of HATT-X has been used in a variety of trials evaluating advanced flight control and attitude and heading reference system (AHRS) algorithms and technologies. In this configuration, HATT-X is capable of maximum flight speeds of Mach 0.9 and flight maneuvers exceeding 5.0g. It has a programmable flight control system that may be readily reconfigured for different hardware and software suites, and is capable of operating in both autonomous and command modes.

Turbojet Configuration - Steps are currently being taken by DRE Suffield to convert two of the rocket-boosted HATT-X airframes into a turbojet configuration powered by the Teledyne-CAE 320-2 engine. The airframe and electronic integration of this engine is being completed by a design team composed of DRE Suffield, Bristol Aerospace Limited, Atlantis Aerospace Corporation, ADGA Systems International, and ATS Aerospace Corporation personnel. After extensive ground and subsystem flight trials completed in 1992-93, the complete turbojet configured HATT-X is expected to undergo its initial flight trials in 1994. The turbojet HATT-X will provide a constant airspeed platform (up to Mach 0.8 in level flight) that will be capable of completing a variety of flight experiments (particularly those associated with guidance and control aspects) for which the boost-glide configuration was not well-suited. In addition, the turbojet configuration will be capable of 30 minute flight times, in comparison with the 4 minutes available for the rocket-boosted configuration.

Air-Launched HATT-X – Some aspects of clearance work for an air launched version of HATT-X, to be released from a CF-5 aircraft, have been completed, and would permit profiles at significantly higher altitudes (greater than 9000 m [30000 ft] MSL) and ranges (75 km plus). All ground tests, including electro-magnetic compatibility and fit/function tests have been completed at the Aerospace Engineering Test Establishment (AETE) at Canadian Forces Base Cold Lake. No work is currently being done on this configuration due to funding constraints.

Miscellaneous Configurations – A number of miscellaneous configurations have been developed or are under consideration, including a stretched fuselage configuration (a 50 cm fuselage plug), re-designed wing and canard planforms that will give the turbojet configuration very high agility at high subsonic speeds, and a number of enhanced flight control features that will permit all-attitude maneuvering of HATT-X.



HATT-X avionics beam with a MicroPilot autopilot undergoing test in the aircraft. The HATT-X autopilot is a research configuration of the MicroPilot system developed for the ROBOT-X POC vehicle by Atlantis Aerospace Corporation under R&D contract to DRE Suffield; Atlantis has a license for the MicroPilot technologies and continues to pursue a number of off-shore markets for this technology.

Suggested Reading

A.B. Markov, C.G. Coffey, and R.W. Herring, Autonomous Unmanned Aircraft R&D with a High Performance Flying Laboratory, First IFAC International Workshop on Intelligent Autonomous Vehicles, U.K., 18-21 April 1993.

A. B. Markov and R. W. Herring, HATT-X: A High Performance Flying Laboratory for Autonomous Unmanned Aircraft R&D, Third Conference on Military Robotic Applications (MRV91), DRE Suffield/Alberta Research Council, 9-12 September 1991.

A. B. Markov and R. W. Herring, Guidance and Control Considerations for a Maneuvering Aerial Target System, Advances in Techniques and Technologies for Air Vehicle Navigation and Guidance, AGARD Conference Proceedings 455, Lisbon, May 1989.

A.B. Markov, C.G. Coffey, and T.E. Ollevier, DRES Rocket-Boosted Target Programs, CASI Flight Test Symposium, CFB Cold Lake, 11-12 April 1984.

A.B. Markov and T.E. Ollevier, Canada Boosts RPV Investment, Defense Systems Review, September 1984.

C.G. Coffey and A.B. Markov, A Rocket-Boosted Sea Launched Target System, Third International Conference on Remotely Piloted Vehicles, Bristol, 13-15 September 1982.

J. L. Lockenour and G. P. Layton, Focus on HiMAT, Astronautics and Aeronautics, Vol. 14, no. 4, April 1976.

ROBOT-X/HATT-X Research Team – The conduct of the ROBOT-X Proof-of-Concept and ongoing HATT-X research flights required the coordinated effort of a number of DRE Suffield sections and R&D contractors to prepare the flight vehicle, conduct the flight, acquire data, to provide for range safety, refurbish flight vehicles and to analyse data.

ACKNOWLEDGEMENT

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